CONVR 2023

Proceedings of the 23rd International Conference on Construction Applications of Virtual Reality

MANAGING THE DIGITAL TRANSFORMATION OF CONSTRUCTION INDUSTRY
University of Florence, Florence, Italy, November 13-15, 2023

edited by
Pietro Capone, Vito Getuli,
Farzad Pour Rahimian, Nashwan Dawood,
Alessandro Bruttini, Tommaso Sorbi

FIRENZE
UNIVERSITY
PRESS

PROCEEDINGS E REPORT
ISSN 2704-601X (PRINT) - ISSN 2704-5846 (ONLINE)
– 137 –

CONVR 2023
PROCEEDINGS OF THE 23RD INTERNATIONAL CONFERENCE ON
CONSTRUCTION APPLICATIONS OF VIRTUAL REALITY
MANAGING THE DIGITAL TRANSFORMATION OF CONSTRUCTION INDUSTRY

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FIRENZE UNIVERSITY PRESS
2023

CONVR 2023 - Proceedings of the 23rd International Conference on Construction Applications of Virtual Reality : Managing the Digital Transformation of Construction Industry /edited by Pietro Capone, Vito Getuli, Farzad Pour Rahimian, Nashwan Dawood, Alessandro Bruttini, Tommaso Sorbi. - Firenze : Firenze University Press, 2023.

(Proceedings e report ; 137)

https://books.fupress.com/isbn/9791221502893

ISSN 2704-601X (print)
ISSN 2704-5846 (online)
ISBN 979-12-215-0289-3 (PDF)
ISBN 979-12-215-0257-2 (XML)
DOI 10.36253/979-12-215-0289-3

Graphic design: Alberto Pizarro Fernández, Lettera Meccanica SRLs
Front cover image: *Ad Alto Angolo Di Paesaggio Urbano,* by Pixabay/Pexels.com, https://www.pexels.com/it-it/foto/fotografia-ad-alto-angolo-di-paesaggio-urbano-208213, CC0 1.0 Universal

The Proceedings of the CONVR2023 are published with the contribution of the University of Florence, which hosted and partially funded the Conference, and Teesside University that collaborated with its organization.

Published by Firenze University Press
Firenze University Press
Università degli Studi di Firenze
via Cittadella, 7, 50144 Firenze, Italy
www.fupress.com

This book is printed on acid-free paper
Printed in Italy

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FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)

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Pietro Capone, Vito Getuli, Farzad Pour Rahimian, Nashwan Dawood, Alessandro Bruttini, Tommaso Sorbi (edited by), *CONVR 2023 - Proceedings of the 23rd International Conference on Construction Applications of Virtual Reality. Managing the Digital Transformation of Construction Industry*,
 published by Firenze University Press, ISBN 979-12-215-0289-3, DOI 10.36253/979-12-215-0289-3

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Foreword

The *International Conference on Construction Applications of Virtual Reality* (CONVR), as one of the world's leading conferences in the areas of immersive realities and digital transformation in AECO Industry, and the local organizing committee are pleased to present the Proceedings of the 23rd International Conference on Construction Applications of Virtual Reality (CONVR 2023) with the overarching theme "MANAGING THE DIGITAL TRANSFORMATION OF CONSTRUCTION INDUSTRY".

The 23rd CONVR was held on November 13-15, 2023, in Florence, Italy and was proudly hosted by the Department of Architecture of the University of Florence.

CONVR 2023 brought together AECO researchers and practitioners from around the globe to report on and exchange the latest development, ideas, improvements and applications stemming from innovative research activities in the following fields: *Virtual Reality (VR) and Augmented Reality (AR), Reality capture and Photogrammetry, H-BIM for heritage management, Simulation and Automation techniques, Computer Vision and Image Processing, Linked Data and Semantic Web for Knowledge Management, Smart Contracts, Distributed Ledger Technologies and Blockchain, Data Science, Machine Learning, and Data-Driven Approaches, Health & Safety, Green and smart buildings, Occupant-centric building design and operation, Building Information Modeling (BIM), Digital Twins, Internet of Everything, Mobile and wearable computing, Construction site management*. Those topics were articulated in eight different areas: *Methodology, Technology transfer, Technology, State of Art, Theoretical Study, Policy and Standardization, Education and Training, Case Study and Application*.

A total of 123 high-quality contributions were accepted after a rigorous review process from 71 esteemed members of the conference's International Scientific Committee. The accepted papers include a total of 374 authors from 32 countries, from Europe, the Americas, Asia and the Middle East.

More than 150 experts attended the conference contributing to enriching the exciting program which included 6 keynote speeches on the first day and 4 parallel presentation sessions on the following days, together with 5 workshop sessions.

The editors trust that this publication is stimulating and inspiring for academics, scholars and industry experts in the field; hoping that this could be a driving force for innovation, growth and global collaborations among researchers and stakeholders. We believe in the significant role that human interactions, networks, knowledge exchange and transfer play in developing high-value and groundbreaking research. This event provides a platform for networking and intellectual exchange of ideas.

We take this opportunity to express our gratitude to the CONVR2023 Technical Organizing Committee as well as our esteemed reviewers and sponsors. The creation of such a broad and high-quality conference program would not have been possible without their involvement and support. We also thank all the authors who dedicated much of their time and efforts to contribute to CONVR2023. We extend our best wishes to you and look forward to seeing you next year for CONVR2024.

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INVESTIGATION OF THE ACCEPTANCE OF VIRTUAL REALITY FOR PLANNING DECISIONS IN EARLY DESIGN PHASES

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ABSTRACT: *In recent years, with the increasing digitization of the construction industry, the potential benefits provided by the adoption of Virtual Reality (VR) have been shown especially in interdisciplinary networking among different stakeholders for which effective communication and information exchange methods are crucial. This is particularly significant during early design phases and associated decision-making processes where, despite its positive impact in terms of project's time and cost savings, VR adoption still has to reach its full potential. For this reason, this paper investigates to what extent the acceptance and application of VR has developed and identifies possible integrations in the early planning phases. By conducting a multi-year study with representatives from the construction industry, including qualitative and quantitative survey methods, the current use of VR and the requirements for future applications are determined. The study reveals that VR's importance for design visualization has increased, identifies architects' current requirements and integration barriers. Additionally, these requirements are compared with existing VR possibilities and an approach for exchanging different variants in a building information model will be examined. Based on these findings, VR can be integrated in application-specific contexts and software can be adapted to architects' needs for optimizing the digitization process.*

KEYWORDS: *Virtual Reality, Decision Support, Early Design Phase, Design Visualization, Study*

1. INTRODUCTION

Virtual Reality (VR) has made significant advancements in recent years and is increasingly being employed across various industries to foster innovative solutions. In the construction industry, VR presents novel opportunities and revolutionizes the approach to project planning, design, and realization (Ozcan-Deniz, 2019). For designers, architects and clients, one of the biggest challenges in the construction industry is the difficulty in visualizing a building project in the early design phase. Traditional methods using 2D drawings and 3D models have inherent limitations in conveying an accurate representation or illusory stimuli (Paes et al., 2017). At this point, VR becomes an important factor. By using VR technology, users are able to enter an immersive virtual environment and experience the future building or infrastructure in 3D. Architects are able to visualize their designs in virtual environments, which enables them to improve their understanding of proportions, designs, and functionalities. Developers have the ability to take virtual tours of their future properties, giving them a realistic feel for the space and amenities. Moreover, VR enables improved collaboration between the various stakeholders in a construction project (Davila Delgado et al., 2020). This allows architects, engineers, developers and other stakeholders to collaborate together in the Virtual Reality environment, make modifications, identify problems and develop solutions even before the actual construction process begins. Besides saving time and money, this may also reduce potential errors and miscommunications.

There are different types of VR technologies, each offering unique approaches to allow immersion in virtual worlds. Tethered VR systems are powerful solutions that require a connection to a computer. They incorporate external sensors or cameras to track the user's movements and ensure precise interaction in the virtual environment (Casini, 2022). Established VR companies such as High Tech Computer Corporation (HTC), META, Valve and Windows are already indicating strong growth in the segment over the next few years (Steam, 2022). Standalone VR devices are autonomous items that do not require a connection to an external computer. Instead, they integrate the display, processor, and tracking technology into a single device and offer a certain degree of mobility and ease of operation. By introducing the Apple VisionPro and its release in 2024, there is a potential for the market in this segment to grow even more in the future, as other technologies from the developer have already had a strong impact on the respective sales market. Mobile VR effectively uses smartphones as displays and processing power for virtual experiences. It allows users to plug their smartphone into a VR headset and access a wide range of VR applications or games (Casini, 2022). Available hardware is suitable for both private and professional applications. Unity, for example, is an applied development environment in architecture for the visualization of VR projects (Boeykens & Gawade, 2013). Due to these market trends, developing technologies and fields of application, it is relevant to investigate the actual potentials and evolution of VR acceptance for the construction industry in Germany. Older studies, such as from the United Kingdom, indicate that integration is imminent in large parts of the construction

Referee List (DOI: 10.36253/fup_referee_list)
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Daniel Napps, Markus König, *Investigation of the Acceptance of Virtual Reality for Planning Decisions in Early Design Phases,* pp. 1-12, DOI 10.36253/979-12-215-0289-3.01

industry (Bouchlaghem et al., 1996), and even more recent studies simply conclude that the AEC industry in the next few years is changing its previous path toward utilizing (Noghabaei et al., 2020). A study from Australia has adopted a similar approach to investigate the adoption of VR in the construction industry. However, this study is limited by a small sample size and the restriction of participants to the community of two universities in Sydney, Australia. As a result, there is no direct assessment of VR adoption among the stakeholders in the construction sector (Ghobadi & M.E. Sepasgozar, 2020). Country-specific surveys on the status of VR in the construction industry are rare, have been conducted many years ago, and do not include any follow-up studies. There is no specific data available for the construction sector in Germany.

Despite its potential benefits, there are several challenges associated with the use of VR for business purpose. Implementing VR technology in the workplace may be expensive, especially the initial investment in hardware and software. Additionally enquires employees to train and understand how to operate the equipment and navigate in the virtual environments effectively (Prabhakaran et al., 2022). VR technology often collects and stores user data, including personal and behavioral information. Maintaining data security and privacy is crucial to protect sensitive information and comply with regulations. To explore these and other similar potential barriers to the widespread adoption of VR in the construction industry, studies have been conducted in various years involving different target groups in the discipline. The study aims to capture the importance of VR for design visualisation in Germany and will explore the current requirements of architects and barriers for integration. A specially created sample application serves as a visual illustration of the VR possibilities and, in addition to the findings from the study, investigates the exchange of different design variants in a building information model.

The structure of this paper is as follows: Section 2 provides an overview of the research approach, presenting the research methodology and providing a supporting visualization for evaluation. The findings from the conducted studies are presented in section 3. In this regard, a categorization is carried out to investigate the potentials of VR on a topic-related basis. Section 4 discusses the findings and provides suggestions for future research.

2. BACKGROUND

2.1 VR in the construction industry

There are many potential applications for Virtual Reality in the early design phases for construction projects. Besides design presentations, simulations, marketing purposes and construction site inspections the collaborative planning is a significant factor. Simulations, for example, can be used to test specific aspects of a project, allowing for customizations to be made according to the building design. Virtual simulations of sunlight exposure provide insights into the materiality of building components (e.g., on the façade), light reflection and consider shadows on surrounding buildings and streets, while rain scenarios help to capture the direct runoff of rainwater on, around, and adjacent to a building in the early phases. For marketing purposes, the early design phase is less relevant. Instead, investors or potential buyers can be shown the project or building in detail, by a digital tour. VR-based construction site inspections allow for the early evaluation of safety measures as well as safety training and later monitoring of construction progress (Zhang et al., 2022). For many of these applications, a BIM interface is beneficial so that modifications can be made and saved directly in the Virtual Environment. These can be than done in virtual spaces, which enable teams from different locations to collaborate virtually on designs and plans, facilitating decision-making and coordination of work processes (Jensen, 2017).

2.2 Acceptance measurement

In terms of the acceptance of the technology in the construction industry, there is a need to operationalize it. For user acceptance, various models such as David's Technology Acceptance Model (TAM) in the field of innovation (Davis et al., 1989) or Kollmann's Dynamic Acceptance Model which was developed to analyze the acceptance of innovative goods can be utilized (Geldmacher et al., 2019). These are commonly applied in the field of information systems technology. According to the latter, the process of acceptance is divided into three levels:

- Attitude level: This level begins with the awareness of a product, which results in the user's interest and expectations.
- Level of action: In the process, the user makes initial tests and experiences that can result in a purchase and subsequent implementation for appropriate utilization.
- Utilization level: Regular access to the product ensures its continued use.

These levels span from the initial purchase decision to actual usage over time. The levels are interconnected, meaning that successful completion of one level leads to the next, ultimately culminating in the overall acceptance of a product. Therefore, assessing the overall acceptance necessitates examining all these levels. In this context, the potentials of the VR technology have a significant impact as they can positively influence the levels and therefore the overall acceptance.

2.3 Variant Management

In the early design phases, architects have various options for designing individual parts of the building. By using the Variant Management, it is possible to store and retrieve different variants for a specific building component in a digital building model. The methodology is designed to provide architects with decision support. This decision support can be advantageous for a virtual and immersive assessment of a project since different options for construction variants can be explored. The Variant Management encompasses three types of variants: Structure Variants, Function Variants, and Product Variants. Structure Variants refer to building elements related to the structure of the building, such as exterior walls. Function Variants are components that fulfill specific functions (e.g., columns), while Product Variants categorize individual products (e.g., windows) (Napps et al., 2021).

At the initial planning process, building elements must be categorized by an architect according to the three variants in order to ensure to find possible design alternatives later on. This categorization of elements into variants can either be done in a BIM software and provided with additional options (Napps et al., 2022) or based on the IFC data. The approach is performed in a graph-based format. Here, the exported IFC file of the model is transferred to a graph representation, whereby IFC entities are represented as nodes and IFC relationships as edges. Possible options are added to an existing variant in form of an option node, which results in the overall graph as a parallel possible option for an element (Napps et al., 2021). VR visualization allows architects to immersively experience the impact of a variant and how it compares to other stored options. If no options are stored in a model, problem-specific features can be specified for a variant in a separate database to obtain possible solutions from other projects as potential options. By choosing an option from another model, the selected option will be automatically stored as an option node to the graph. The selection of a design option can stem from either a calculation of similarity to other variants or on a specific aspect of investigation. Recently, Variant Management has been used to carefully evaluate design options or alternatives for cost efficiency and assessed alternatives to building components based on their costs to identify the optimal solution for a project (Napps et al., 2023).

3. RESEARCH DESIGN

The research design consists of primary research involving online surveys and expert interviews supported by a literature review to identify the current status and potentials of VR and its use in the early design phases. In order to investigate the current integration and acceptance of VR in the construction industry, a study over several years is conducted, as well as a determination of the acceptance of the technology among potential stakeholders. Acceptance has an important impact, as it is directly related to the usage. An identification of affected actors in the construction industry, the reduction to research-relevant stakeholders and the identification of actual potentials and the operationalization of acceptability is therefore necessary (Fig. 1).

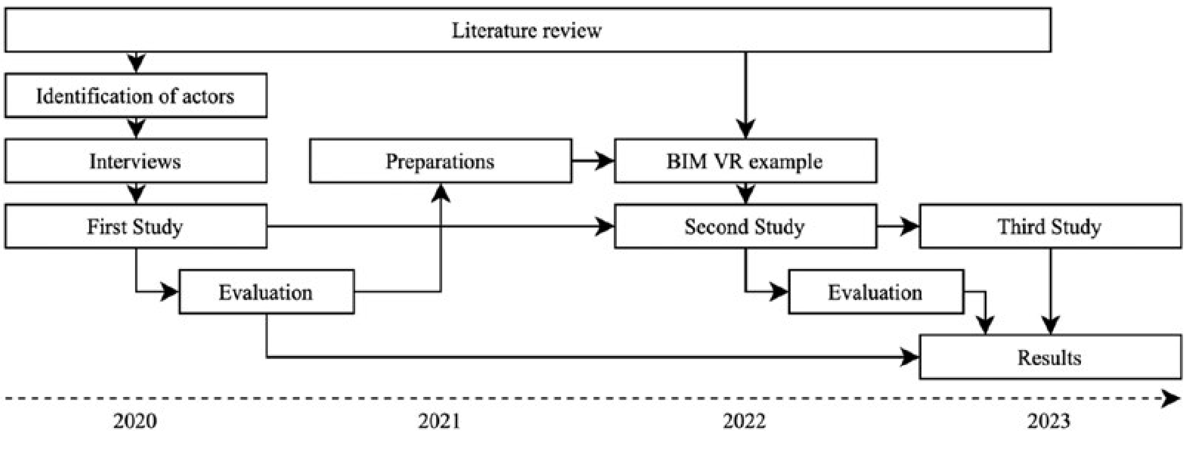


Fig. 1: Research design schedule.

In the construction industry, there are multiple stakeholders working together who might benefit from cooperation and coordination via VR in projects. This includes primarily architects, who have to consider the planning concept, the design wishes and ideas based on the requirements of the clients and on legal circumstances. A planning agency is a service company in which civil engineers, specialist engineers and planners work together. Geographers, geometricians and geoinformatics potentially can come into contact with VR in the planning process, for example, when it comes to generating city or terrain models or data bases. Real estate developers and investors are equally important actors who benefit from early visualization of the project in VR for new buildings, as well as for renovations and modernizations. Municipalities occupy a significant position due to the facts that, on the one hand, they have the primary role in the planning process in Germany, and on the other hand, they are highly significant as contractors for architects and investors (Emmitt, 2010). Of these, smart cities are highlighted, which are characterized by their significantly more innovative character compared to other municipalities. Furthermore, the public benefits from project renderings in VR, as they are able to receive a 3D visualization of the planning through the public participation required by law in Germany (§ 3 Abs. 1 BauGB) and do not have to rely on a planning knowledge of 2D plans and views.

Due to the limitation to the early design phases because of the increased relevance for planning decisions and error minimization (Østergård et al., 2016), not all of the mentioned stakeholders are of equal importance for potential usage and acceptance determination. Therefore, these are to be reduced due to the observation scope. In this context, the decision was made to specifically target architects and also gain insights into the overall sentiment of German cities. This approach allows for capturing aspects from both the supply side (architects) and the demand side (municipalities). Volunteers from the population were also invited to take part in a survey, as the Planning Act in Germany provides that they must be involved in construction projects and plans. For the identification of potentials, different assumptions resulting from research with regard to advantages and disadvantages for the use of VR were analyzed and summarized. These were formulated in various forms into neutral closed and open questions as much as possible.

3.1 Interview

In this research, the integration of interviews and surveys offers a broader and more comprehensive approach to gather data. Whereas interviews have a minor role in this study, they are instrumental in obtaining qualitative data and gaining deeper insights into individual experiences, which subsequently informed the design of the survey questionnaire (Rafidah Biniti Ab, Rahman, 2023). By combining these research methods, the results can be validated and triangulated, enhancing the overall reliability and credibility of the data and the interpretations made.

Table 1: Overview of the interviewees.

	Year	Date	Leading questions	Gender	Country of origin	Field of expertise
Interview 1	2020	7th July	16	female	Germany	PhD and urban researcher in the context of the digitalization of cities
Interview 2	2020	13th July	17	female	Austria	Focus on urban development and public-private partnerships in digital context
Interview 3	2020	16th July	18	male	Switzerland	Software developer for mixed reality and cloud computing
Interview 4	2020	12th August	14	male	Germany	Honorary professor and member of a progressive digitization network
Interview 5	2020	14th August	12	male	Austria	Chief marketing officer of an augmented and Virtual Reality startup
Interview 6	2020	2nd September	10	female	Switzerland	Focus on Digital Real Estate and member of an innovation team

At the outset of the study in 2020, interviews were conducted with specific stakeholders to shape the questions for the study and gather initial insights into the adoption, application, potentials, and barriers of using Virtual Reality in the construction industry. A total of six individuals from different disciplines were selected for expert interviews at various professional levels, which are shown in Table 1. Care was taken to include individuals with technical understanding, as well as scientific and practical knowledge of working with Virtual Reality in the construction industry. The six interviewees were equally distributed among the fields of software development, academia, and urban management and marketing (Tab. 1). All of them had experience with urban-level projects or collaboration with authorities responsible for planning. The experts represented both Germany and other European countries. The duration of the interviews, guided by specific questions, was approximately 60 minutes each. Starting with general topics, the discussions moved on to concrete questions about example projects and the involved actors. Due to partial critical comments on the topic and missing consents of personal data, the experts are anonymized.

3.2 Study

Quantitative research uses standardized surveys to collect data for a large sample size of individual people, groups of people or institutions. The methodology is used to analyze and describe mass phenomena. Online surveys are characterized by their monetary advantage, location independence of the respondents and low temporary effort of collection and evaluation (Mellinger & Hanson, 2021). No related data is stored in the questionnaires, which ensures honest statements and opinions. The questionnaires were initially distributed individually to different groups of persons (Planning and architectural offices) and later by a random principle, e.g., with the help of the inclusion in the newsletter of the Federal Chamber of Architects of North Rhine-Westphalia. The surveys were provided as an online survey and sent via link to the appropriate contacts. Three surveys were conducted over the course of three distinct years, with each survey period lasting approximately six weeks. The initial survey was carried out in July 2020, followed by a subsequent survey in July 2022, and a third in mid of July 2023 (Tab. 2).

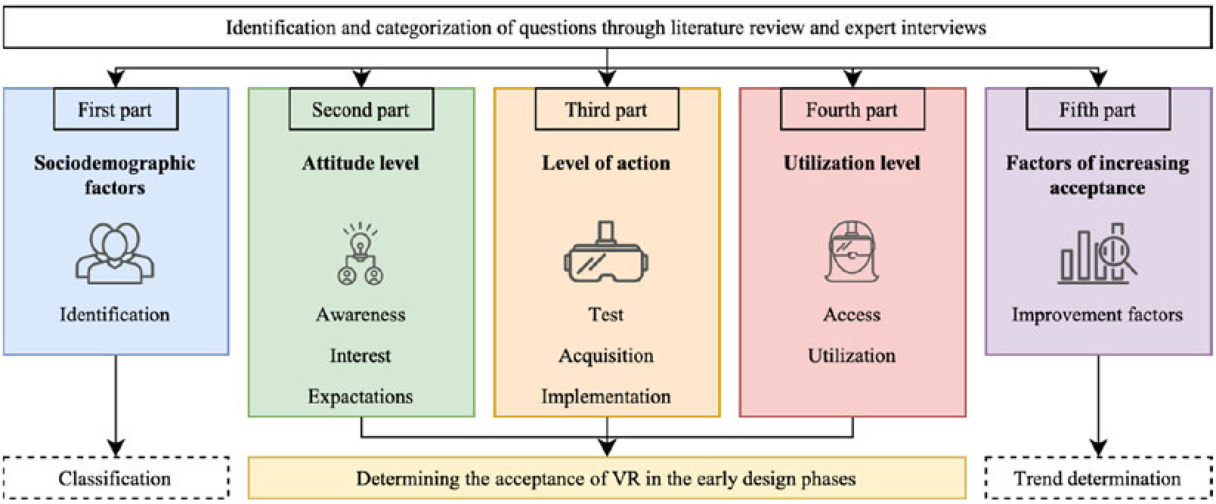


Fig. 2: Structure of the first study according to the acceptance measurement and for the evaluation of trends.

The first study from 2020 was a large-scale study, a deliberate combination of closed (yes/no) questions and open-ended questions was used to capture the situation of Virtual Reality in the construction industry as accurately as possible from different perspectives (Fig. 2). For the first study in 2020, different municipalities and smart cities were drawn from a sample of all German cities. Based on the cities identified, planning offices were selected in each case. Due to the significance of public participation (§ 3 Abs. 1 BauGB) and the benefits identified in the literature, the survey was conducted among both the identified stakeholders in the construction industry and a small sample of the population in Germany. In total, the first study thus consisted of four individual surveys. The sample size was chosen equally for the first three categories (Tab. 3). One follow-up reminder email was sent after half of the survey period.

Table 2: Overview of the studies.

	Year	Questions	Question type	Participants	Country of origin	Estimated duration	Objective
Study 1	2020	16	Mixed	60 + 55	Austria, Germany, Switzerland	12min	Large-scale data acquisition
Study 2	2022	19	Mixed	53	Germany	10min	Data acquisition for comparison
Study 3	2023	9	Closed	11	Germany	3min	Data acquisition for trends

Although the second study was conducted for the use of BIM and Variant Management, it includes a thematic block on VR. Therefore, the second follow-up study aimed to capture potential changes and trends in the adoption and acceptance of VR in the field. The last study was designed to collect final determining factors and is still ongoing. Only single choice questions were used in the third survey to compare most significant factors for the success or failure of VR integration and adoption with the previous ones. Actually, the survey period of the last one has not yet ended. The number of questions varied depending on the study. Overall, the studies were designed with a range of 6 to 16 questions. For the last one, a lower number of questions was used to ensure quick completion by the participants. However, the structure always followed a systematic framework, starting with the general use of VR for projects, followed by exploring advantages and disadvantages, as well as other criteria for measuring the potentials and acceptance. The questions were selected according to the operationalization of acceptance and divided into corresponding categories. In this regard, besides dichotomous and multiple-choice questions, Likert-scale survey questions and question types such as ranking and matrix questions were predominantly employed. A total of (60 (+ 58 participants from the general Population) + 53 + 11) participants were involved in these multi-year's studies, whereby it is to be mentioned that not all respondents answered each question. An overview about these studies is shown in Table 2.

3.3 Experimental realization of the Variant Management in VR

The study was supported with images to enhance participants' understanding of the use of Virtual Reality in the construction industry (Fig. 3). Towards this intent, a building was created which also served as an evaluation example to explore any potential opportunities and barriers in the realization of a project, focusing on the adaptation of a building design in VR. The building information model was created in Autodesk Revit and exported to Unity for visualization in a virtual environment (Fig. 3a). Utilizing the Unity Reflect Review enables design validation before and during a project. For this purpose, various options for building elements were modeled, such as different window variations, doors, and facade options (Fig. 3b & 3c), allowing architects to experience the changes in the building from both the interior and exterior perspectives. This approach aligns with the practical work of architects who evaluate different design variants for a building in early design phases and experience modifications in 3D to gain a better understanding of the effects of different building elements (Fig. 3d).

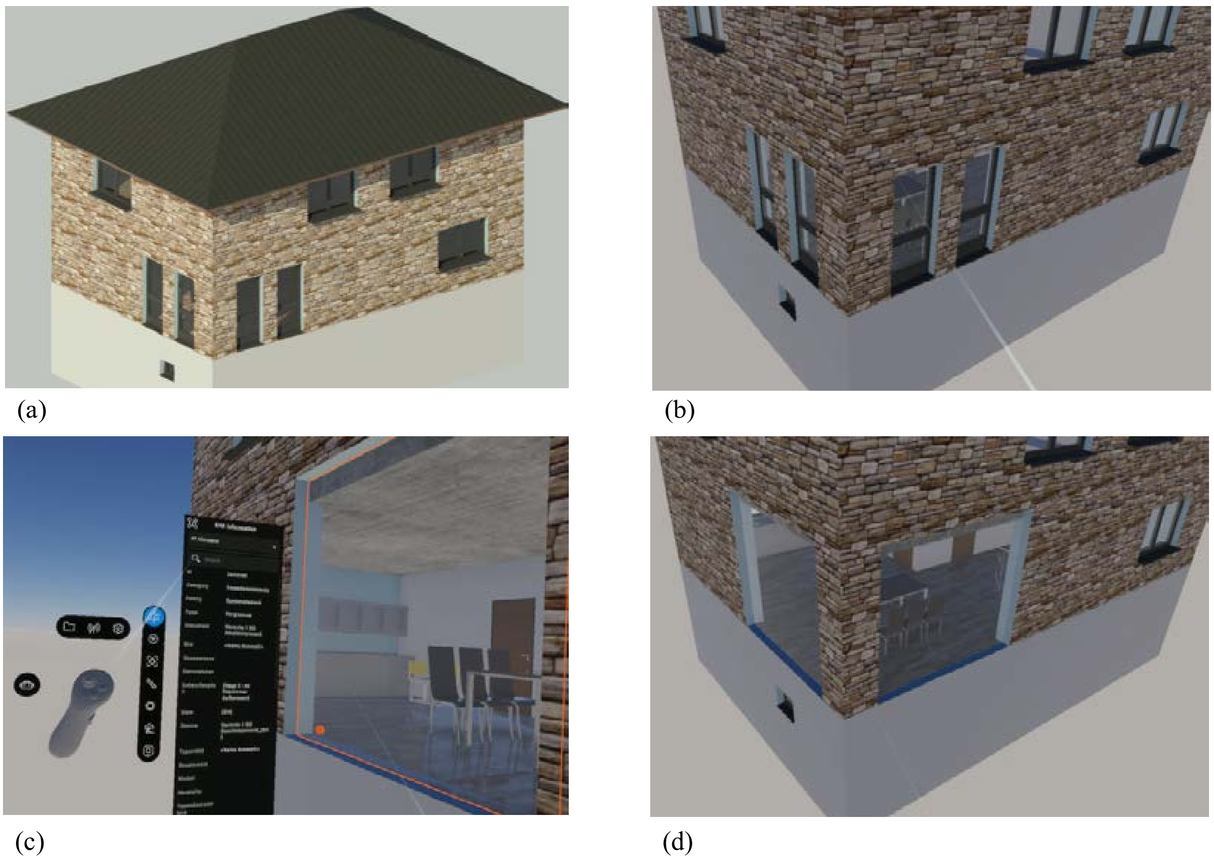


Fig. 3: (a) Building information model, (b) Building design variant in Unity, (c) Checking for stored design options with information and live interaction (Oculus Quest 2), (d) Customization and comparison.

4. FINDINGS

The initial study aimed to explore the current state, potentials, and acceptance of Virtual Reality (VR) in various sectors of the construction industry. To achieve a comprehensive understanding, the study included not only planning offices but also municipalities, smart cities, and segments of the general population in Germany. The subsequent two follow-up studies, however, narrowed their focus to examine planning offices primarily. This decision was driven by the fact that planning offices play a central role in the planning phases, whereas municipalities, smart cities, and the population are more closely associated with the final outcomes of completed projects. The results are categorized in sub-sections to facilitate comparisons of the studies. A total of 182 responses from the studies can be evaluated for this purpose. The three acceptance levels are considered in the discussion.

For the findings, the abstentions were mostly omitted from graphical representation to maintain clarity. The evaluation of the study is divided into three parts. Beginning with an assessment of VR's awareness and integration in the construction industry, it is followed by an exploration of its potentials and barriers. Findings regarding the creation of the VR example project, including various design options and the implementation are shown afterwards. In the discussion, the level of acceptance of VR technology in the construction industry is presented in the context of the demonstrated measurement process.

The response rates for the first study, illustrated in Table 3, range from 28% to 48%. Additionally, 58 individuals from the population participated. Incomplete responses to questions were not included in the response rate and were also excluded from the results. For the subsequent studies, voluntary participation was encouraged among different offices, because the response rate was the lowest in 2020. Based on a large-scale study examining 8,672 surveys and 1,071 online surveys in educational research, a weighted average response rate of 44.1% for online surveys in educational fields was identified (Wu et al., 2022). Different online survey platforms indicate an acceptable response rate between 5% to 30% and values above this correspond to a very good response rate (Chung, 2022; Le Masson, 2023). In the study from 2022, there were several abstentions on some questions, which resulted in the lowest rate for answering a specific question at 41 out of 53 participants (77.3%). All questions for the year 2023 were completed.

Table 3: Response rate of the first study 2020.

	Sample	Incomplete responses	Complete responses	Average time needed	Response rate
Municipalities	50	23	19	approx. 6min	38%
Smart Cities	50	37	24	approx. 7min	48%
Planning and architecture offices	50	16	14	approx. 6min	28%
Population	-	-	58	approx. 5min	-

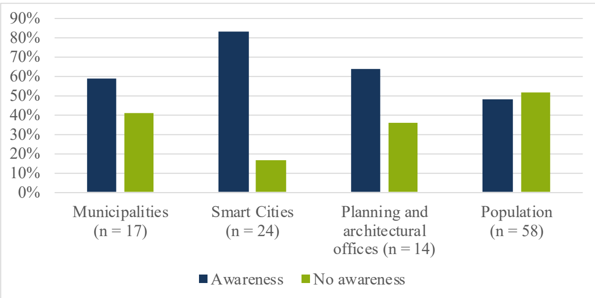
4.1 Actual awareness and integration

The study reveals that both awareness of Virtual Reality for the use in the construction industry and the resulting potential work experiences vary among the surveyed groups. It is evident that the majority of direct planning stakeholders (Municipalities, Smart Cities, and planning and architectural offices) are aware of the application of VR in this context, while the general population is more divided. The division among the public was already suspected during the interviews, as one expert from the scientific perspective believes that citizen participation regarding the acceptance of the technology is currently most advanced, while the software expert is of the opinion that the public is still unaware of it all. However, all interviews indicated that awareness among the population is increasing with a growing number of VR projects, and through the gamification factor, the usage and involvement of the population in projects can be enhanced. Some pilot projects from practitioners can confirm this impression.

Concerning Smart Cities and municipalities, the experts assumed that they are already aware of the technology, but the adaptation processes are challenging. The interviewees with practical background are already familiar with cities that work on projects in VR, but they point out that Smart Cities are likely to take the lead, while other municipalities may wait and observe these developments. However, it is said, that there is a general interest in the topic. It is also noted that larger cities might have a higher interest than smaller towns. Out of 24 respondents, 20 (83.3%) demonstrated the highest awareness of VR technology and its application in favor of Smart Cities, whereas 10 out of 17 municipalities (58.8%) showed awareness of the technology (Fig. 4). Two municipalities did not reply.

Regarding the planning offices, a relatively low penetration of awareness and the resulting integration and application was predicted by the interviewees before the study. First movers would take the lead here, but the technological novelty would not initially revolutionize conventional planning processes. Offices that deal with renderings at a high level are said to experience increased interest, as it enables them to maintain or even improve quality standards. Among the surveyed offices, 9 out of 14 (64.3%) had heard of VR (Fig. 4), and 5 out of 9 (55.5%) had already worked with it (Fig. 5), indicating a high level of awareness and practical experience. Regarding to the work experience, among Smart Cities and municipalities, the percentages were 50% and 30% (Fig. 5). In relation to their previous awareness levels, with municipalities having the lowest percentage of work experience.

The study from the year 2022 depicted that the utilization of VR for the actors within architectural and planning offices is nearly 10% higher than in 2020. According to the 2023 study, this positive trend is not continuing, as 54.5% of these offices report that they have already integrated VR into their everyday work (Fig. 7). This indicates that the level has adjusted to the 2020 level. However, the willingness to use it (71,4% in 2020) continues in a moderate form in 2023 (54,6%).



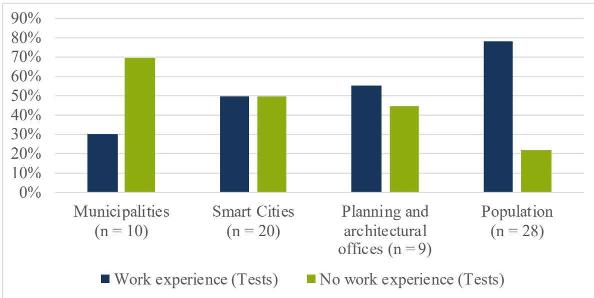
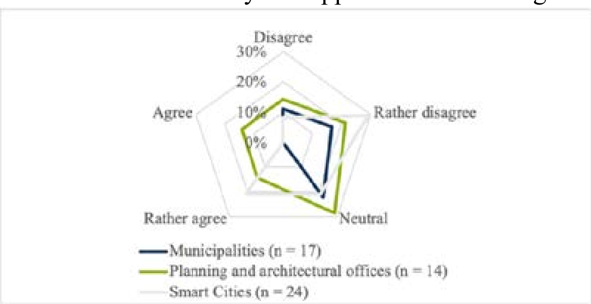


Fig. 4 (left): Comparison of the awareness (2020).

Fig. 5 (right): Comparison of the practical experience (2020).

Interest in the utilization was captured by questions regarding the willingness to incorporate Virtual Reality into the daily work routine and is shown in Figure 7. With the aid of an example integrated into the questionnaire, even participants who were previously unfamiliar with its application could partake in the question. As a result, it becomes apparent that 31.6% of the surveyed municipalities are ready to use VR in the near future, and 63.2% are neutral and do not reject the possibility of potential future adoption. Among Smart Cities, 50% express a willingness to use VR, with no direct rejections. As for the planning firms, 42.9% of the respondents have an interest in its utilization only 2 out of 14 offices do not want to use VR in future. In the year 2022, a highly positive trend was observed regarding the financial benefits derived from the implementation of technology among these actors (Fig. 7). One disadvantage, however, is the readiness of the hardware, which negatively affects the potential utilization. This primarily concerns the urban stakeholders, as five municipalities (26.3%) and six Smart Cities (25%) are not willing to provide hardware for meetings with other stakeholders, while one office (7%) is unwilling to do so (Fig. 7). The experts also perceive the provision of hardware, especially for small offices and small cities, as challenging. Experts in technology hinted in 2020 that with the introduction of Apple's proprietary software, both the general population and the cities and planning offices would benefit since these devices would reach a certain level of maturity and appeal to a broad range of citizens.



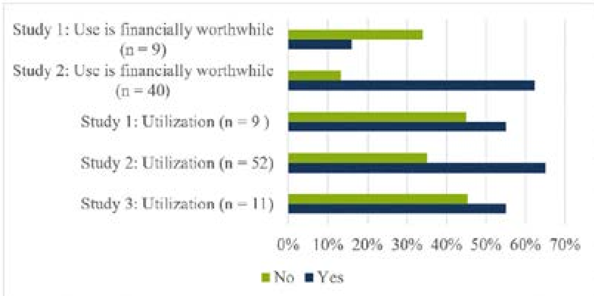


Fig. 6 (left): Comparison of the potential utilization (2020).

Fig. 7 (right): Comparison of the utilization propensity and financially worthwhile for offices (2020-2023).

As the potential utilization is related to the expectations of the technology, these expectations were also collected accordingly. For this purpose, three categories were identified, and the respondents were asked to indicate the extent to which they agree with each statement. Despite some negative remarks, the expectations regarding VR are predominantly aimed at achieving more efficient workflows with other stakeholders, improved communication, and increased public participation. The 2023 results confirm that, but reveal that respondents overwhelmingly agree that the use of VR in the construction industry is neither in high nor low demand. However, most respondents (72,3%) agree that VR representations have a high impact on the construction industry.

4.2 Identified potentials and barriers

The assessed potentials arising from the utilization of VR in the AEC industry are contrasted with the barriers encountered based on diverse experiences, offering a comprehensive comparison. Various response options identified in the literature and the interviews were given to capture the potentials and barriers for integrating Virtual Reality in the construction industry, with multiple responses allowed. The results primarily stem from the extensive study conducted in the year 2020. Trends are being verified with the two additional studies.

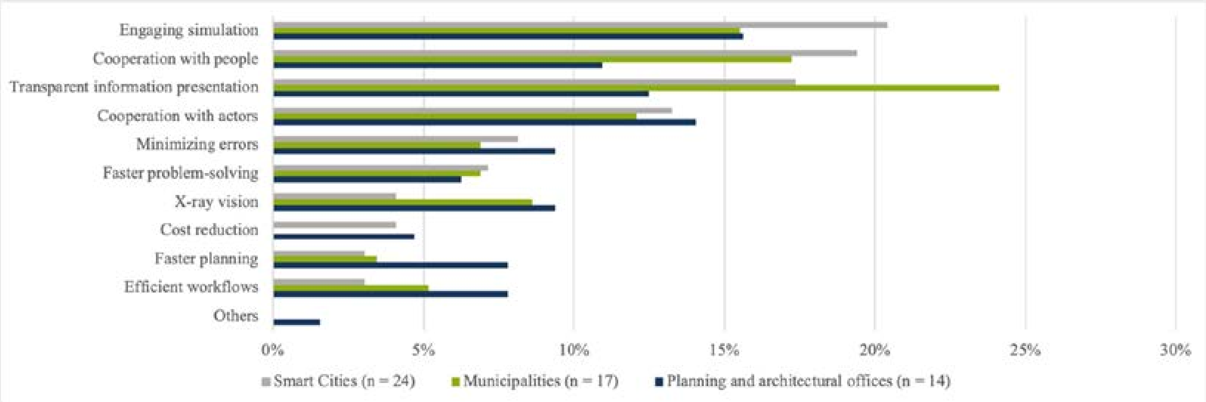


Fig. 8: Results of the first study on the potentials of the use of VR in the construction industry.

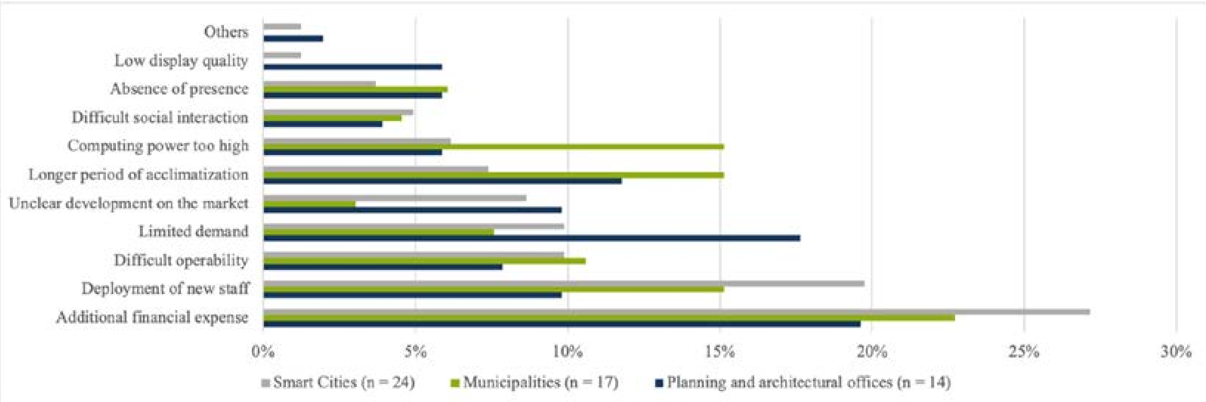


Fig. 9: Results of the first study on the barriers of the use of VR in the construction industry.

The most significant advantage, cited by 71.4% of planning offices, is the ability to create appealing simulations, followed by nine offices (64.3%) that agree to the advantage in better collaboration with other planning stakeholders (Fig. 8). Error minimization gained the greatest advantage among respondents in 2023 (36,4%). As the most significant disadvantage (71.4%), these stakeholders mention the financial burden. The two additional studies also confirm, with the highest number of agreements, the potentials of VR for simulation and collaboration, identified as the greatest potential for planning offices and their respective stakeholders. Additional monetary expense remains the most important barrier factor across the board, even within the study group (Fig. 9).

The three most significant potentials of the municipalities are transparent presentation of information (24.1%), improved collaboration with the population (17.2%), and the creation of appealing simulations (15.5%) (Fig. 8). The most significant barriers are the financial burden (22.7%), followed by the potential need for hiring new personnel, longer adaptation time, and the requirement for high computing power, each cited by 15.2% (Fig. 9).

For Smart Cities, the potentials are in the same three categories but with different weights (Fig. 8). The potential areas are transparent presentation of information (17.6%), improved collaboration with the population (19.4%), and engaging simulations (20.4%). As barriers for the integration of VR in the construction industry, the major concerns are the financial expense (37.3%), the need for hiring new personnel (27.1%), and challenges in operating the technologies as well as a low demand (13.6%) (Fig. 9).

In the study, the indicated potentials, based on the cumulative votes, outweigh the cumulative number of votes for the barriers.

4.3 Practical implementation

During the implementation of the Variant Management for visualization in VR, minor obstacles initially emerged, as saved building options cannot be stored directly in the software environment. Instead, only the selected variant is saved as a Revit file. In consequence, two versions of the designed building had to be saved for the visualization, each with different variants selected. Finally, the visualization is performed with Unity Reflect Review.

Another complication occurred attempting to use the Revit files directly in Unity Reflect Review, as the Unity Engine does not support the Revit format (.rvt). Alternatively, saving the file in the format (.fbx) facilitated the export and import of 3D objects, 2D objects, light sources, cameras and materials between Autodesk software programs and, since 2017, also between Unity. However, the object is displayed generically and in grey because Unity does not recognize the materials from Revit. Manual input of new materials that are recognized by the Unity library does not include all Revit materials and proves to be too time-consuming. Solving the problem is to alternatively use the IFC file for the two models and import it into Unity. A script then allows the BIM metadata to be retrieved and displayed within the object by having the script read the elements' information from the IFC file. It is important that the IFC file comes from the same 3D model referenced by the FBX file.

5. DISCUSSION

The studies have demonstrated that among the examined direct planning stakeholders, there is a predominant awareness of VR for planning processes. Many of these respondents also exhibit an interest in usage, some of which has even slightly increased. They highlight significant expectations of VR for planning tasks, aligning with the identified current capabilities. The results of the first study indicate that several municipalities, half of the surveyed Smart Cities, and the majority of the surveyed planning offices have already worked with and tested VR. While the willingness to acquire suitable hardware was generally portrayed as positive in all studies, the highest barrier, particularly for planning offices, was the financial extra expenditure. In terms of implementation progress in daily operations, a positive trend can be observed from 2020 to 2022. However, the results from 2023 potentially suggest a plateauing. It should be noted, however, that the study does not reflect the total number of offices, so the results from 2023 should rather be understood as a sample for trends. The provision of hardware is accompanied by the already examined acquisition. The willingness to use VR is strongly pronounced among the examined stakeholders, and the potential provision of hardware for meetings with other stakeholders is partially available. Ultimately, the utilization rate over the years demonstrates a significant practical application of VR, even though it appears to be slightly declining in 2023. This trend could potentially be attributed to a lack of demand for VR implementation in projects from contractors (cities and investors), for instance. Regarding the application, some experts see the advantage in the mobile use of VR, as it lowers the entry barrier and in the developments of the products and integration in a broad market. Overall, it can be observed that there was a solid basis for the acceptance of VR in the construction industry for planning decisions, which has continued to grow over the years. The majority of the sampled planning and architectural offices exhibit attitudinal (Level 1) and application (Level 2) behavioral acceptance. However, because utilization (Level 3) depends on certain factors, such as personnel, acquisition, strategic planning and access the acceptance of usability in 2020, is present in less than half of the offices. However, the subsequent studies have shown that the utilization of VR has not declined, which has led to the fact that the third level of acceptance has now also been reached by the majority. Among the smart cities, there was already an overall acceptance in 2020, according to the results of the majority of respondents, whereas the municipalities were not yet able to achieve an overall acceptance at that time, due to a lack of awareness, the resulting lack of test phases and a low willingness to invest. This results in poor values for this actor at all three levels of the acceptance measurement.

While the mentioned potentials and barriers indeed prevail, an individual weighting of factors is not feasible. For instance, a barrier might be so formidable that it cannot be overcome, as exemplified by the purchase of software for small design firms or cities. Nevertheless, the results of the assessment of monetary readiness for the adoption of VR software in comparison to its benefits have demonstrated that numerous architects and engineers have been able to enhance the integration and implementation of VR. By surveying the barriers among the different stakeholders, it was possible to identify factors for increasing the acceptance of VR for the visualization of planning in early design phases, which can be addressed accordingly from the developer perspective as well as the user perspective in further research.

The provided example has demonstrated that visualizing digital buildings in Unity using the IFC format of a model is straightforward, while the exchange of design alternatives with the Variant Management is a bit difficult. In the future, an alternative approach could be explored to better integrate the stored options in this regard. Visualizing projects in the early design phases provides added value for stakeholders, and there is a recognizable public interest in VR visualization of the final product for public information activities and cooperation with other stakeholders.

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BUILDING INSPECTOR XR: STREAMLINING SCAN-TO-BIM WITH VIRTUAL AND MIXED REALITY

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ABSTRACT: *Digitalization in the construction industry is increasingly striving to create digital twins in order to continuously exploit optimization potential in the management and utilization of existing buildings. Building Information Modeling (BIM)-based as-is or as-built documentation represents a promising basis in this context, which requires creating a geometric model for example based on point clouds as well as semantic enrichment in a Scan-to-BIM workflow. Conventionally, this is carried out manually by specialists on 2D screens and often is time-consuming and costly. The project "Building Inspector XR" addresses these issues and presents an intuitive solution for BIM-based as-is/as-built documentation using X-Reality (XR). In Virtual Reality (VR), BIM models are created off-site from point clouds and then are verified in Mixed Reality (MR) on-site. By integrating (partially) automated methods and targeting user-friendliness in our solution, Scan-to-BIM can be realized more efficiently and intuitively. In this paper, the focus lies on the innovative aspects of our XR application which encompass VR and MR environments, automation support, modeling schemes in compliance with BIM standards, and the registration of models in reality for MR. Additionally, the paper shows the interconnected toolchain that facilitates an efficient Scan-to-BIM workflow.*

KEYWORDS: *Building Information Modeling, Virtual Reality, Mixed Reality*

1. INTRODUCTION

The global and cross-industry trend of digitalization is increasingly shaping the construction industry as well. As a comparatively less digitalized industry, there is a great need for the development and implementation of digital methods in the construction industry in particular. The linchpin of the digital transformation in the construction industry is the cooperative working methodology Building Information Modeling (BIM). Compared to traditional methods, BIM offers the potential to improve communication and coordination between all construction stakeholders, make management for cost and time more efficient, and achieve higher levels of detail in digital building models by incorporating component-specific semantics in addition to geometry. Although the use of BIM is applicable across the entire lifecycle of buildings, in reality the collaborative working methodology is predominantly used for new structures. For existing buildings, BIM has not yet been applied frequently, although it could create added value for operation and utilization by enabling the resulting digital as-is/as-built models to be used to represent and evaluate the existing condition of the building and, based on this, to plan possible maintenance measures, carry out simulations or organize issue management more efficiently.

For the application of BIM in this context, it is first necessary to capture the existing buildings. In most cases, such an acquisition process is carried out by means of laser scanning (terrestrial or mobile) or photogrammetry. The result of these procedures is a 3D point cloud. The subsequently necessary process of generating a digital building model from the available point cloud is summarized under the term "Scan-to-BIM" and is currently mainly implemented manually on two-dimensional screens using keyboards and mice. Therefore, we identified the need to improve the Scan-to-BIM process, by making it more intuitive in a 3D space using X-Reality (XR). In this paper, we present the project "Building Inspector XR", which includes both a Virtual Reality (VR) and Mixed Reality (MR) application, for the intuitive creation of as-is/as-built BIM models based on existing point clouds.

2. BACKGROUND

2.1 Reality Capturing

As a holistic approach to documenting structures, BIM places more far-reaching demands on building surveying. To meet these requirements, various methods of reality capturing are employed, including photogrammetry, terrestrial laser scanning and mobile laser scanning.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Christoph Blut, Tristan Kinnen, Jörg Blankenbach, Dirk Heidermann, Felix Schellong, *Building Inspector XR: Streamlining Scan-to-BIM with Virtual and Mixed Reality*, pp. 13-22, DOI 10.36253/979-12-215-0289-3.02

Photogrammetry is a method of deriving geometric information of an object from images (Luhmann, Robson, Kyle, & Boehm, 2014). A distinction is made between mono- and stereo-photogrammetry. While mono-photogrammetry is based on the analysis of single images, stereo-photogrammetry uses pairs of images to measure objects, such as buildings. Using photogrammetry, areas that are difficult to access can be surveyed with a comparatively high information density with Structure from Motion/Dense Image Matching. The respective achievable geometric accuracy is subject to a number of factors, such as the camera technology, the resolution of the individual images, the type of reference point determination (Donath, 2008) and specifically the image scale.

In addition to photogrammetry, laser scanning forms another practical method for building acquisition and is considered the leading technology for the acquisition of 3D spatial information with high density (Lari, Habib, & Kwak, 2011). From a functional point of view, a distinction is drawn between laser scanners with impulse and phase measurement methods. Impulse measurement determines the time of flight of the laser beam, while phase measurement evaluates the phase shift of the reflected signal. While laser scanners with the phase comparison method are characterized by a significantly higher number of recorded points per second, laser scanners with the impulse measurement method offer a significantly higher range. Terrestrial laser scanning is characterized by stationary acquisition of local 3D data of the object from different locations and subsequent registration of the data of all locations relative to each other. In contrast to this, mobile laser scanning continuously acquires 3D data while the object is in motion and registers the data via positional information.

The output of each of these methods is a high variety of 3D points representing the respective surface of the acquired object. These 3D point clouds can be used for further analysis and modeling.

2.2 Scan-to-BIM

In addition to the surveying workflow, the holistic BIM approach to the acquisition, management and exchange of building information also has implications for the processing and modeling of data (Blankenbach, Schwermann, & Becker, 2021). The process of creating or reconstructing as-is/as-built BIM from 3D point cloud data is called Scan-to-BIM. For this process, individual geometric elements such as walls, doors or windows are initially created on the basis of the point cloud data. Additionally, to the geometric model, attributes such as materials, dimensions or further semantic information are linked and documented to the corresponding objects. Subsequently, the resulting BIM model is validated and checked for possible errors or inaccuracies to ensure compliance with requirements and standards. Currently, this process is predominantly handled manually by professionals using (3D) computer-aided design (CAD) or BIM authoring software, such as Autodesk Revit (Autodesk, 2023). While automated solutions for this process are being progressively developed in both research and industry, each of the currently available off-the-shelf Scan-to-BIM software packages presently still requires significant manual user input making the entire process cumbersome and error prone (Son, Kim, & Turkan, 2015).

2.3 State of the art

(Adekunle, Aigbavboa, & Ejohwomu, 2022) compiled a systematic literature review network analysis on the topic of Scan-to-BIM in 2022. According to this, Scan-to-BIM is being researched worldwide with a view to finding more efficient solutions, which occasionally also include the use of VR and AR technologies for information management. However, specific works are not mentioned since the paper focusses to summarize, categorize and analyze the different topological backgrounds and their nationally backgrounds. Therefore, no specific work for modeling in VR or Augmented Reality (AR)/MR is addressed. (Wu, Hou, & Zhang, 2021) and (Alizadehsalehi, Hadavi, & Huang, 2020) show studies that aim to compile various publications related to BIM and XR applications. (Wu et al., 2021) outlines a BIM-XR application as a system combining a BIM database and a human-machine interactive interface for context-aware visualization and interaction. Generally, it highlights that XR can enable modifications and updates to the BIM model and offers intuitive visual representations and interactive experiences within the BIM context. However, the study primarily emphasizes the visualization aspect and does not present detailed approaches for geometric and semantic BIM modeling in VR or MR environments. Specifically, the focus is on AR/MR for post-construction BIM model adjustments, while VR is considered mainly for visualization purposes. (Alizadehsalehi et al., 2020) discuss the benefits of XR technologies for construction project simulation and present a comprehensive overview of XR applications. Nevertheless, while acknowledging the potential of using XR with BIM for interactive visualization, the study focuses on approaches to transform pre-designed BIM models into XR rather than intuitive modeling in VR and MR.

Commercial products such as Enscape (Chaos, 2023) or Twinmotion (Epic Games, 2023a) allow a visualization of 3D models in VR as well as creating images, animations or walkthroughs, however, both require importing previously created models and do not provide the possibility of modeling, except for simple drag and drop functions via the desktop computer editor, in VR. Further XR possibilities, such as the transformation into AR or MR, are also not possible. In comparison to our solution, VR Sketch (VR Sketch, 2023) presents a similar approach. Nevertheless, it lacks comprehensive BIM capabilities, making it incapable of conforming to BIM standards when modeling components. Moreover, the software does not support point clouds. Arkio (Arkio, 2023) offers a platform specifically developed for collaborative design and architectural conception, focusing on free geometric modeling in a VR environment. For this, existing BIM models and 2D plans can be imported as a data basis and the created 3D geometric models can be exported into selected BIM authoring software, such as Autodesk Revit or BIM360. However, Arkio does not provide BIM-specific functionalities to ensure BIM-compliant (as-built) modeling, like complying with existing standards, providing standardized component catalogs or semantic enrichment. Also, Arkio is limited to proprietary file formats and does not contain the option of exporting to the open Industry Foundation Classes (IFC) (buildingSMART, 2019) standard. 3D models can also be created and edited in AR, but this feature is limited to tabletops. GAMMA AR (GAMMA Technologies S.à r.l, 2023) on the other hand offers the possibility to overlay BIM models on construction sites. This integration aids in error prevention and precise component monitoring. Nonetheless, it does not support actual modeling activities. BIM Holoview (BIM Holoview Ltd., 2023) combines VR and AR/MR to enable users to view BIM models using Meta Quest 2 (Meta, 2023) and Microsoft HoloLens (Microsoft, 2023). However, it is limited to Autodesk 3D Revit and Navisworks files, restricting modeling functionalities. Unity Reflect (Unity Technologies, 2023) encompasses the broadest range of capabilities. It allows users to view BIM models in various ways, including VR, AR/ MR, on multiple devices, nevertheless, it does not support the creation of BIM models in real-time.

3. METHODOLOGY

The Building Inspector XR revolutionizes the process of building inspection by harnessing the power of VR and MR technologies. This chapter presents an overview of the process chain involved in the Building Inspector XR, covering its architecture, hardware and software choices, and the functionalities it offers. Through the utilization of point clouds and BIM models, accurate pose tracking, and seamless integration of virtual content into the physical environment, the Building Inspector XR system streamlines the Scan-to-BIM process.

3.1 X-Reality for Scan-to-BIM

The XR BIM system is the foundation of the Building Inspector XR. Fig. 1 illustrates the system's structure, where a point cloud, generated through photogrammetry or laser scanning, serves as the initial data in VR. With the point cloud as a context, the user creates a BIM model, which can be exported as an IFC file for interoperability or brought into MR for on-site enhancement. This seamless interchangeability between VR and MR enables efficient workflows, supporting models based on the IFC building and waterways domain. Choosing the right hardware and software is crucial for the success of an XR system. For the Building Inspector XR system, the Valve Index (Valve Corporation, 2023) and the Microsoft HoloLens 2 were selected. The Valve Index, a tethered VR headset, provides high-quality pose tracking necessary for accurate movements in VR. On the other hand, the Microsoft HoloLens 2 was chosen for its MR capabilities, including accurate pose tracking, gesture-based interactions, and immersive visuals. Software plays a significant role in the Building Inspector XR system, with Unreal Engine (UE) (Epic Games, 2023d) serving as the development framework of choice. UE offers a broad application field beyond gaming, supporting various file formats and a wide range of hardware, including the Valve Index and the Microsoft HoloLens 2. The system leverages relevant plugins to extend its functionalities, such as the Datasmith Plugin (Epic Games, 2023c) for importing IFC files and the LiDAR Point Cloud Plugin (Epic Games, 2023b) for importing point clouds. The open source nature of UE allows for customization and modifications to the core engine functionalities.

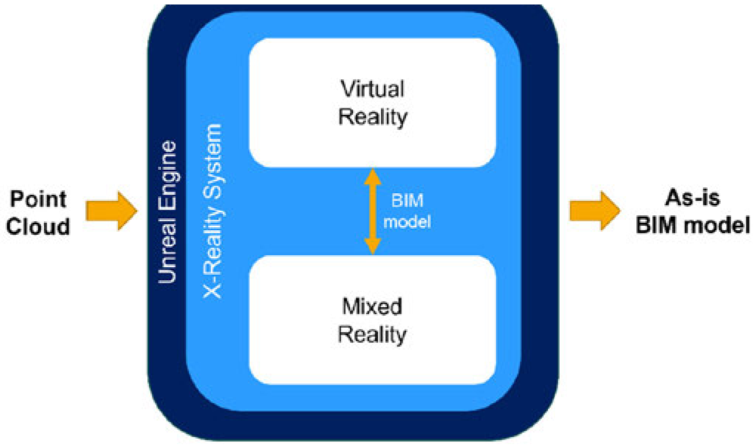

Fig. 1: Architecture of the Building Inspector XR.

The LiDAR Point Cloud Plugin on the one side offers an import interface and on the other side point cloud rendering methods to visualize the point clouds in UE. For starting the modeling process in XR, the initial point cloud can be provided in a couple of different formats, such as XYZ, PTS, LAS/LAZ or E57. Once available in the system, multiple parameters of the LiDAR Point Cloud Plugin ensure that the point clouds are rendering efficiently. We configured the plugin so that the point clouds are visualized with the highest quality possible, while maintaining a high performance. A highly detailed presentation of point clouds is crucial, so that as much information can be derived from the data as possible during modeling. Like this, small details of the environment can be already identified and modeled from the point clouds, enhancing the value of the BIM model, and minimizing additional modeling work later in MR or post processing (Fig. 2).

Fig. 2: Point cloud in VR.

In XR, but especially in VR, rendering performance is crucial for a smooth and realistic user experience. A high frame rate of 90 frames per second (FPS) or higher is recommended to reduce motion sickness and enhance the overall user experience. To address the challenge of rendering large amounts of data, optimization techniques are employed. These include an efficient octree data structure and spatial partitioning. Level of Detail (LOD) systems are used to reduce complexity as objects move farther from the camera, improving performance. The VR system provides intuitive interactions for easy BIM model creation. The VR controllers enable users to access the menu attached to the left controller and interact within it. Over the menu all required functionality to create a complete BIM model is accessible to the user, including geometry and semantic data modeling methods, editing tools and export functionality. The right controller is reserved for the actual modeling process. Teleportation allows instant movement to designated spots in the virtual environment, while fly-mode enables reaching higher locations. Pose tracking allows physical movement within smaller areas, accurately replicated in the virtual environment.

In contrast to VR, the MR system of the Building Inspector XR does not require a complete virtual world (Fig. 3). Instead, it integrates the virtually modeled objects into the physical environment. This is specifically challenging, because the virtual elements modeled in VR need to be placed as accurately as possible in reality, so that they overlay their physical counterparts. Like this, the user can inspect elements, for instance by comparing the modeled with the real situation. Also, details can be added to the BIM elements, for example additional attributes such as material or even further geometric information. This is important, if objects or details were not visible in the point cloud, either because they were covered by other objects during reality capturing or too small so that they are hardly or not visible in the point cloud.

Fig. 3: MR application.

Accurate alignment between the virtual and physical worlds is achieved through pose tracking, which seamlessly integrates the virtual and real elements. The system employs a Visual Simultaneous Localization and Mapping (V-SLAM) algorithm on the Microsoft HoloLens 2 for accurate pose tracking. This algorithm keeps track of the user's pose (position and orientation), thus, of the Microsoft HoloLens 2, keeping virtual objects robustly anchored to a location in reality. To achieve an initial accurate alignment between the virtual objects and reality, a registration method is employed. The Building Inspector XR system utilizes the Kabsch–Umeyama algorithm (Umeyama, 1991), a widely used method for aligning and comparing similarity between two sets of points in multidimensional space. The goal of the algorithm is to find the optimal rigid transformation matrix that aligns one set of points to another set of points. It can roughly be broken down into three steps:

1. Calculate the centroids of both point sets.
2. Transform both datasets to the origin and then calculate the required rotation.
3. Calculate the required translation and scale.

For MR registration, this can be used by defining corresponding points in the virtual world and reality. Optimally, points are chosen that can easily be identified in both spaces, for instance the corners of a door or window (Blut & Blankenbach, 2021). We therefore provide the means for users to actively select corresponding points in the BIM model and in reality. The gesture-interaction system of the Microsoft HoloLens 2 allows easy and intuitive point selection using fingers. And with the spatial understanding of the Microsoft HoloLens 2, points can accurately be placed in reality. Since the points need to correspond to each other, we provide numbered spheres that simply must be placed in the desired spots by drag-and-drop interaction (Fig. 3). Once all spheres have been placed, the user only needs to confirm to perform the instant alignment. This referencing process can be repeated as needed to maintain accuracy.

Once virtuality and reality have been aligned, the user can start the inspection or modeling process. Due to the head-mounted nature of the Microsoft HoloLens 2, the user has both hands free for interactions. We provide a floating menu with the same UI and functionalities as in VR, so that creating a BIM model is as intuitive in both spaces but optimized for the technology. Creating and interacting with objects using Microsoft HoloLens 2 is as easy as using the point or pinch-gesture.

3.2 BIM-compliant as-is/as-built modeling

By combining VR and MR, the Building Inspector XR enables the creation of models completely in 3D space. Furthermore, modeling as well as interactions are carried out intuitively by gestures and voice input. In terms of functionality, we placed emphasis on advanced geometric modeling, linking semantic object data, and compliance with standards for ensuring a standardized BIM model (as-is/as-built model). Within the scope of the associated research project, we focused on the as-is/as-built BIM modeling of building as well as water engineering structures.

The Building Inspector XR offers users three different approaches to geometric modeling, tailored to the complexity of physical objects. The first method is free modeling (Blut et al., 2023). Simpler objects like rectangular walls, floors, or ceilings can be created by specifying just two diagonally opposite points and the software automatically generates a solid object with parallel edges. This method ensures quick and precise modeling. For objects with more intricate geometry, the parametric modeling feature is available. Users input a minimal set of parameters, from which all the necessary geometric information is derived. Step-by-step instructions guide the users through the process. For example, when modeling a ladder, the user only needs to input the base point, height, and width, with adherence to relevant standards such as the German DIN 18799 for fixed ladder systems on structures. The DIN 18799 specifies that the width of a ladder may be between 400 and 600 mm and that the distance between the ladder rungs must be between 225 and 300 mm. Furthermore, it defines that the first and last rungs should be at least 100 mm and a maximum of 400 mm from their respective ends of the ladder. When the user inputs the required parameters, these value ranges are considered. If any value exceeds or is below the permitted ranges, the respective upper or lower limits are set as new modeling parameters to ensure that the modeled object is in accordance with the prevailing standards. Based on the resulting dimensions of the ladder, the two side rails are first created, and then the number and positions of the individual rungs are automatically generated, considering a standard-compliant entry and exit spacing of 200 millimeters.

In cases where manual modeling proves challenging due to the complexity of the object, the Building Inspector XR provides an integrated catalog of pre-modeled components. These components come with essential attributes and can be easily dragged and dropped into the desired positions. This feature significantly speeds up the modeling process, particularly for highly complex objects. For example, a niche bollard can be quickly inserted using this method (Fig. 4). To enhance modeling capabilities further, the Building Inspector XR enables users to selectively cut out areas defined by the user using Boolean operations. This allows for the insertion of additional components or modifications to existing objects.

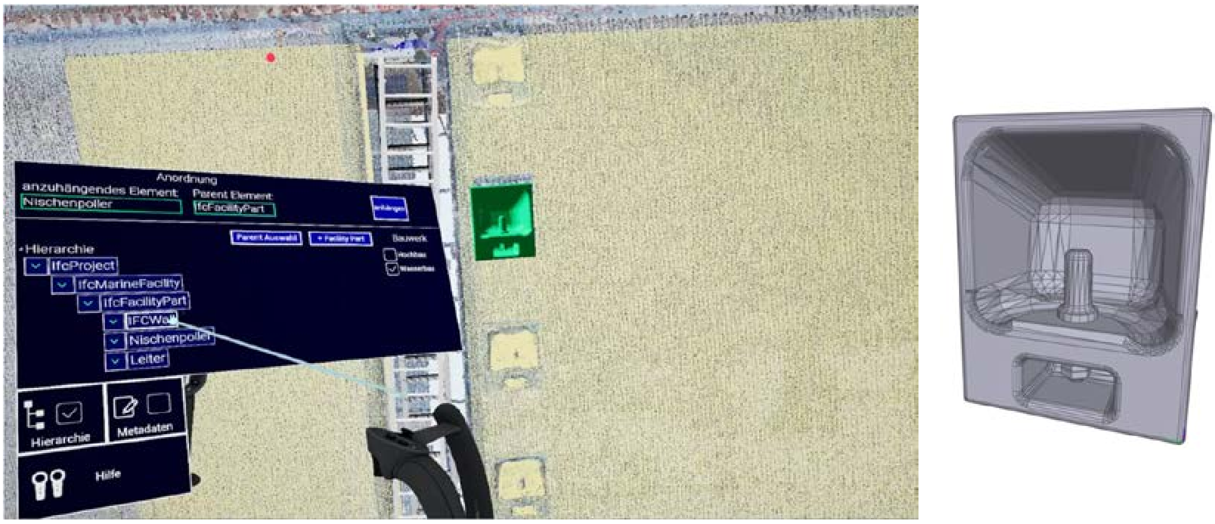

Fig. 4: Placing pre-modeled IFC components in the scene.

A plane fitting algorithm assists users in accurately placing objects on a plane, ensuring proper alignment between components and reducing modeling time. For the detection of surfaces the Random Sample Consensus (RANSAC) algorithm is used. The goal is to find, in several iterations, the area where the largest number of points from the point cloud lie in a plane, i.e., where the distances of all points to the respective plane are minimal, by randomly selecting three points to form a plane in each iteration. Then, the distances of the remaining points to the plane are determined. The plane of the best iteration is stored. RANSAC ensures that outliers are effectively eliminated (Fig. 5).

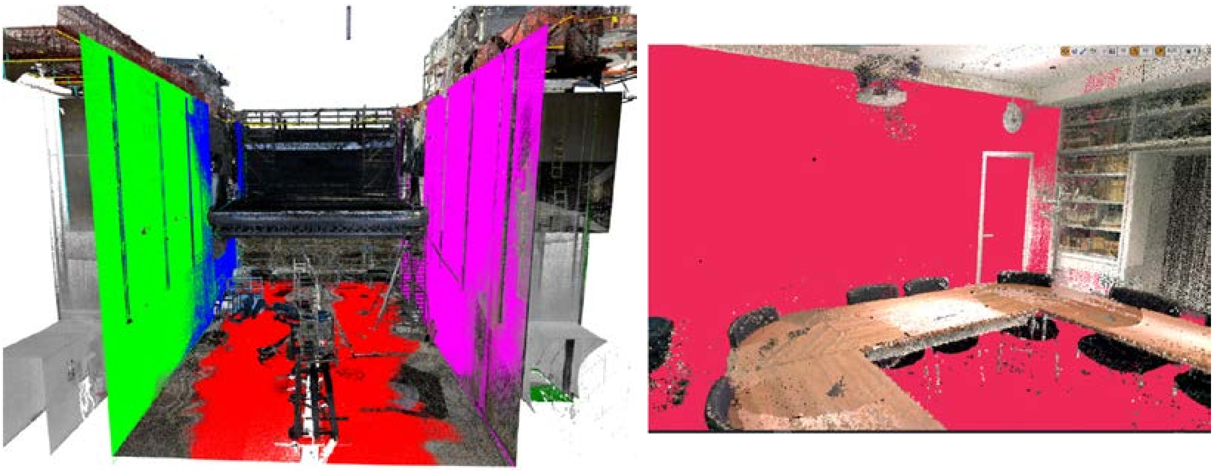

Fig. 5: Detected planes using the plane detection algorithm.

The Building Inspector XR not only focuses on geometry but also emphasizes the assignment of semantic data to objects. By adopting the IFCx4.3 (buildingSMART, 2023) standard as its data model, the software ensures compliance with BIM standards throughout the modeling process. Users can input specific attributes such as name and description for each object, and additional information can be freely assigned using IFC's property sets. The software follows a clear hierarchical structure, enabling users to classify objects, create object-specific properties, and assign components to the IFC hierarchy. Adhering to the IFC hierarchy is crucial for effective BIM implementation. Furthermore, it ensures that modeled objects are correctly classified and organized within the BIM model, facilitating efficient data exchange and collaboration among project stakeholders. The IFC data model is reflected 1:1 already in the application, so that BIM models can easily be exported without loss of data. This was solved by creating the corresponding IFC classes in UE and placing them according to the place in the IFC hierarchy in the UE scene graph. When the user during the modeling process creates a new object, this object can be filled with attributes according to the standard and placed as a parent or child of other objects.

Moreover, the Building Inspector XR facilitates the export of the completed BIM models in the standardized IFC (IFCx4.3 standard) format. The resulting IFC file in STEP Physical Format (IFC-SPF) is readable in any IFC-compliant software, allowing for visualization, editing, and extension of the model using BIM viewer or BIM authoring software.

The integration of water engineering structures into the Building Inspector XR further enhances its versatility and applicability in various construction projects. Users can now model, analyze, and visualize not only buildings but also water engineering elements such as locks, dams, and canals. The inclusion of these new IFC classes demonstrates the commitment to providing a comprehensive XR BIM solution that caters to a wide range of construction disciplines.

4. BUILDING INSPECTOR XR IN PRACTICE

In this section the practical experience with the Building Inspector XR is described. To evaluate the Building Inspector XR, we modeled an office. To obtain the base data for modeling, first, the office and the surroundings of the office were captured with the geodetic terrestrial laser scanner Riegl VZ400 and contained 21 million points (Fig. 6). Subsequently, the resulting point cloud was cleaned from outliers and unnecessary data and exported as a LAS file, since the format proved to work well with the UE LiDAR Point Cloud Plugin. With LAS, importing goes quickly and all data is transferred correctly. On a computer with an AMD Ryzen 9 3900X 12-Core Processor with 3.80 GHz, 32 GB RAM and a M.2 SSD, the LAS file could be imported in less than a second. Importing the same point cloud in E57 format took roughly 20 seconds.

Fig. 6: Point cloud from terrestrial laser scanner of an office in the Building Inspector XR.

A model was created in VR and then later transferred to the Microsoft HoloLens 2. The registration method for aligning the virtual world with reality proved to be efficient, so that the previously modeled objects overlayed their physical counterparts accurately. Three corresponding points were used. The distribution of these three points across the room was crucial, so that an optimal transformation could be calculated. Therefore, we placed on point in the corner of the room, one point on the other side of the room on the corner of a window and the third point on the corner of the door in the wall between the first two points. This provided the maximum distribution of points in the room. The resulting alignment had an accuracy of under 1 cm. After modeling, the BIM model was exported as a IFC-SPF. The created BIM model, i.e., the resulting IFC file then could be loaded without problems in different BIM viewers, such as BIMvision (datacomp, 2023).

The evaluation showed that the Building Inspector XR has a distinct advantage over professional and highly complex BIM authoring software. Inexperienced users could effortlessly create IFC-conforming models using this system. The immersive nature of VR and MR played a significant role in this achievement as it made handling virtual tools and dealing with complex data like point clouds and IFC models much more accessible. Users found the interface intuitive and were able to interact with the models in a natural manner, similar to real-world interactions. The users' experiences revealed that certain modeling tasks, particularly those involving large objects, were most efficiently performed in VR. The flexibility of locomotion in the virtual environment allowed for quicker and more fluid modeling. On the other hand, when it came to adding finer details and object-specific information, the MR application proved to be more advantageous due to its ability to provide better context for these additions. One notable result of the system's efficiency was the ability to model a substantial structure in only a short time. This speed and ease of modeling emphasized the system's capability to create BIM models in a highly efficient manner. Overall, the combination of VR and MR in the XR BIM system demonstrated its potential to empower users, regardless of their experience level, to produce accurate and conforming BIM models in a more intuitive and time-effective way.

5. CONCLUSION

With the Building Inspector XR, we aim to enhance the Scan-to-BIM process by developing an efficient workflow that incorporates VR and MR, ensuring the creation of BIM-compliant as-is/as-built models in a standardized IFC structure, which includes the latest state of the art and thus in addition to building construction also water engineering classes. By transferring BIM to VR and MR, integrating automation, implementing modeling schemes based on BIM standards, and facilitating model registration for MR, we have successfully developed a more intuitive workflow in this context, as users can experience a more immersive and interactive environment for modeling and inspecting existing structures, especially using XR technologies.

For now, we have focused on building and water structure engineering with a selection of elements, therefore, the current capabilities of the Building Inspector XR do not cover all structure types and components but demonstrate the efficiency of our approach. We believe that the Building Inspector XR has the potential to expand its applications in the construction industry. By leveraging artificial intelligence, opportunities to automate modeling tasks can be explored, improving efficiency and reducing human error. In addition to progressively expanding the functionalities of the Building Inspector XR, the inspection aspect, in particular, holds significant promise for further development and extension. To validate and refine the solution, further testing and implementation in real-world scenarios is essential. This would provide valuable insights into the effectiveness and practicality of the Building Inspector XR in real-world construction projects and enable further optimizations and adjustments based on feedback and requirements.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support of the German Federal Ministry for Economic Affairs and Climate Action in the project "Entwicklung eines virtuellen Bauwerksinspektors zur Erstellung von BIM-Modellen in VR/AR (Bauwerksinspektor XR)" (grant number 16KN093501)

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THE VALUE OF EXTENDED REALITY TECHNIQUES TO IMPROVE REMOTE COLLABORATIVE MAINTENANCE OPERATIONS: A USER STUDY

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ABSTRACT: *In the Architecture, Engineering and Construction (AEC) sector, data extracted from building information modelling (BIM) can be used to create a digital twin (DT). The algorithms of a BIM-based DT can facilitate the retrieval of information, which can then be used to improve building operation and maintenance procedures. However, with the increased complexity and automation of the building, maintenance operations are likely to become more complex and may require expert intervention. Collaboration and interaction between the operator and the expert may be limited as the latter may not be on site or within the company. Recently, extended reality (XR) technologies have proven to be effective in improving collaboration during maintenance operations, through data display and shared interactions. This paper presents a new collaborative solution using these technologies to enhance collaboration during remote maintenance operations. The proposed approach consists of a mixed reality (MR) set-up for the operator, a virtual reality (VR) set-up for the remote expert and a shared Digital Model of a heat exchanger. The MR set-up is used for tracking and displaying specific information, provided by the VR module. A user study was carried out to compare the efficiency of our solution with a standard audio-video collaboration. Our approach demonstrated substantial enhancements in collaborative inspection, resulting in a significative reduction in both the overall completion time of the inspection and the frequency of errors committed by the operators.*

KEYWORDS: *Virtual Reality; Mixed Reality; Operation & Maintenance; Collaboration; Digital Twin*

1. INTRODUCTION

From all the new methodologies and technologies brought by the latest industrial revolution known as Industry 4.0 (I4.0), some of the most explored in the last years are Digital Twins (DT) and eXtended Reality (XR) technologies (Augmented Reality (AR), Mixed Reality (MR) and Virtual Reality (VR)) (*Gartner Top 10 Strategic Technology Trends for 2023*, 2023; Jamwal et al., 2021). Numerous studies have already proven that these technologies can improve industrial performance, but also building exploitation. A previous work has been done to summarize all these improvements, focusing on the ones brought to maintenance procedures in the Architecture, Engineering and Construction (AEC) sector (Coupry et al., 2021). It has been shown that data extracted from the building information model (BIM) can be used to create BIM-based DT. Such DT can be likened to a centralized database where real-time and static data of an equipment can be gathered and retrieved or used to predict the equipment behaviour and, thus, to compute the optimal maintenance time. Thanks to the centralization offered by a DT, different stakeholders can participate more actively in maintenance procedures, adding equipment-specific information or even checking it before maintenance is needed. In this context, XR devices can be used by on-site operators to display this information in front of the equipment, giving them access to the data needed to perform a maintenance operation.

However, occasionally, the on-site operator may require more specific assistance in resolving certain issues he or she may encounter. The increased complexity of systems and procedures, brought about by I4.0, may necessitate contacting a remote expert. Such assistance may also be required in the case of maintenance work on equipment with which the operator is unfamiliar. With the impact of Covid-19 and the increasing costs of transport, it is now needed to provide new methods for remote collaboration with an expert. XR devices can be used to provide meaningful information on both sides of such a collaboration. Either using virtual representations or shared video,

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Corentin Coupry, Paul Richard, David Bigaud, Sylvain Noblecourt, David Baudry, *The Value of Extended Reality Techniques to Improve Remote Collaborative Maintenance Operations: A User Study,* pp. 23-33, DOI 10.36253/979-12-215-0289-3.03

the XR devices provide remote experts with contextual information, such as the position and orientation of the on-site user in relation to the inspected equipment. These devices also provide advanced methods to display information to the on-site user, either through localized annotations or specific data related to the equipment.

Speech communication is the most common method of information exchange during a remote collaboration. Visual cues, such as sharing visual context, are crucial to enhance collaborative performance. Such information can be obtained through 3D reconstructions, which can be static (Kolkmeier et al., 2018; Piumsomboon et al., 2017) or in real-time using depth sensors (Bai et al., 2020; Gao et al., 2016). To scan the, though, specific cameras are typically required. Furthermore, if any changes were made since the last capture, the static models' reliability decreased, which also affected the accuracy of the information shared with the expert. Sharing view has also been explored, either by limiting the expert's perspective to that of the operator (Serubugo, 2018), or by using 360° video, which provides real-time information while allowing the expert to move his vision freely, independently from the operator's (Teo et al., 2019). A 360° camera is thus required, which could burden the on-site operator unnecessarily.

Oral exchange and sharing context are not the only elements required for a good collaboration, visual aid is also important. While some researchers found that the use of annotations (Anton et al., 2018; Fakourfar et al., 2016) can be helpful to share specific location or elements, others observed that sharing gaze (Bai et al., 2020; Piumsomboon, Dey, et al., 2019) can help the collaborators to understand where everyone is looking. Sharing gestures has also been studied and proved to be useful for specific manipulations, such as assembly tasks or localisation issues (Chenechal et al., 2016; Wang et al., 2019). The use of a 3D avatar to show the user's movements and position has also proved to be helpful in increasing performance and decreasing the mental effort of the operator (Piumsomboon, Lee, et al., 2019). A method is proposed by (Grandi et al., 2019), allowing asymmetric collaboration between two users using handheld both AR or VR devices. Even if users could manipulate a 3D model to complete docking tasks, this system allows interactions only with a virtual object, not a physical one. Another work by (Ladwig, 2019) allows a VR user to interact with the 3D representation of a suitcase/machine. Each action performed by the VR user activates a LED to the physical to inform a local user which action to perform. This solution comes closest to using a DT to assist a field operator. (Oda et al., 2015) used so called *"virtual replicas"* to communicate between VR and reality. These replicas are copies of tracked physical machine parts that are rendered accordingly at the correct position in the virtual environment in relation to the machine. Wang et al. have already shown of these virtual replicas can be used to improve remote collaboration by projecting the remote expert gestures to the local operator (Wang et al., 2023). However, projection is not always possible due to lightning issues or narrow operating spaces.

The solution proposed in this work draws its inspiration from all these projects. It consists of a new system where a remote expert and a local operator can both use real-time audio-video feedback and 3D models to interact with each other. The system is using collaboration techniques from both *asynchronous* (checking explanations beforehand) and *synchronous* (physical positions of the operator and the system) collaboration systems. A user study has been conducted on the impact of this solution during a collaborative remote inspection of a heat exchanger. The inspection consists of several manipulations, requiring both one-handed and two-handed operations. The rest of this paper is organized as follows. In Section 2, the framework of our solution is presented. Section 3, describes the user study performed to validate the usability of the solution, followed in Section 4 by the analysis of the results. In Section 5, these results are discussed. Finally, Section 6 presents the conclusions and thoughts on the remaining work to be done on the solution.

2. FRAMEWORK

2.1 Prototype setup

The prototype solution design focuses on binding both audio-video exchange and immersive 3D interactions into a single cross-platform solution. This solution uses MR and VR to connect a local operator with a remote expert for real-time remote interaction. We implemented the solution with Unity3D and C#. Our audio-video exchange protocol is built upon Web Real-Time Communications (WebRTC) library (*WebRTC*, n.d.). The solution consists of a MR client and a VR client, both based on the same application. The Photon Unity Networking (PUN 2) plugin is also used to allow the remote expert to share specific information with the local operator (*Photon Unity Networking*, n.d.). Fig. 1 shows the overall setup of the project. Our solution is developed using the OpenXR norm, allowing our solution to became cross-platform (*OpenXR*, 2016). In Fig. 1, the "BIM-DT" section represents a BIM-based DT. It consists of the shared 3D representation of the physical twin, a history database containing semantic data and the results of previous operations, and a sensor database, where all the data collected from the physical twin is stored (see Fig. 1, red arrow). The BIM-DT also contains a simulation model, with which the VR and the MR user can interact if necessary to simulate specific situations or procedures. This uses data from both databases.

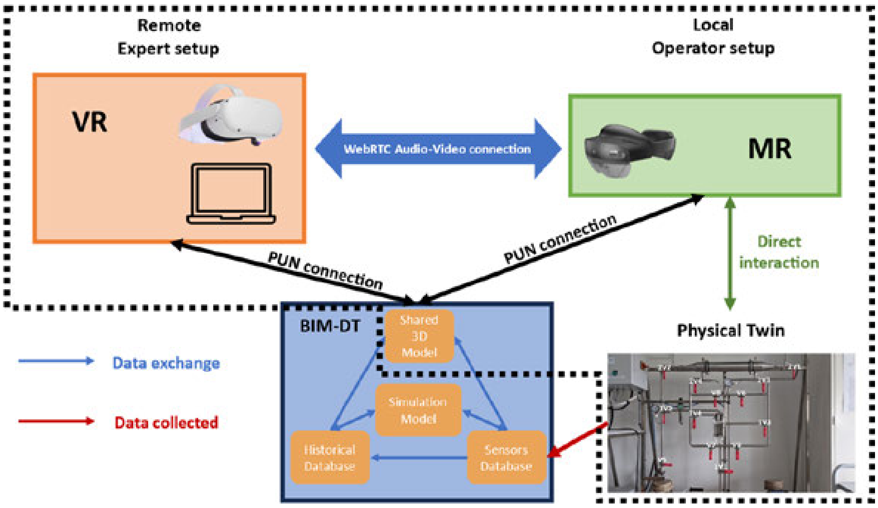

Fig. 1: Schematic representation of the proposed setup consisting of (left) remote expert setup, with VR device and computer, (right) local operator setup, with MR device and physical system, and (bottom center) the BIM-DT.

The local operator side consist of the physical twin of the system (cf Fig. 1 “Physical Twin”), on which the maintenance is performed, and a Microsoft Hololens 2 (Microsoft, n.d.-a) to use the MR client of our solution (cf Fig. 1 “MR”), developed using the Mixed Reality Toolkit (MRTK) provided by Microsoft. The local operator will be referred to as the *Operator* for the remainder of this paper. The remote expert side consist of a Meta Quest 2, wired to a VR-ready laptop PC (Intel Core i9, 32GB RAM, Nvidia RTX 3080), running the VR client of our solution, through Oculus Link connection (cf Fig. 1 “VR”). The rendering capabilities of the PC can manage and host the network connection between the HMDs. The Windows Device Portal (WDP) web server can also be used by the remote expert to record the conversation with the *Operator*, using the Mixed Reality Capture function provided. The PC also host a node-dss server for the WebRTC connection between the VR and the MR clients. The remote expert is also provided with specific documentation on how the maintenance should be performed on the system. The remote expert will be referred to as the *Expert* for the remainder of this paper. The *Expert* and the *Operator* are located in different rooms in the same building during the collaboration. An audio-video exchange is provided between both clients using the WebRTC protocol, which provides peer-to-peer real-time audio and video communication for collaborative applications (see Fig. 3. (blue arrows for *Operator*, red arrows for *Expert*)).

2.2 Information exchange paradigm

2.2.1 3D representation

A 3D model representation of the system is implemented. This model is loaded only on launch, for the VR client, or when a specific QR code is identified, for the MR client, using a specific SDK developed by Microsoft (Microsoft, 2022). Once the QR code is found, the 3D model is loaded in relation to its position. The model is shared between the MR and the VR client and contains the scripts allowing the exchange of information between the two clients, using the PUN plugin. This plugin provides us with a specific feature called *Remote Procedure Calls* (RPCs), allowing each client to call methods on remote clients in the same room. This feature has enabled us to set up an asynchronous interaction system for our solution. The PUN plugin also allows us to create avatars to represent both clients. The avatars used are composed of a white sphere with makeshift glasses, to inform the other client where each avatar is looking. This representation of the users allows for a better communication between them (Piumsomboon, Lee, et al., 2019). In our case, we have decided to use a *God point of view* situation, where the *Expert*’s avatar is on a higher Y-level than the *Operator*’s one, allowing the *Expert* to see where the *Operator* is placed in the physical space in relation with the physical system (Piumsomboon et al., 2017).

2.2.2 Replica paradigm

Our asynchronous interaction system is using the *Replica* method for interactions. Based on the concept of *Voodoo dolls*, brought by Pierce et al, this method consists of creating a reduced copy of a 3D model instead of a direct interaction with it (Pierce et al., 1999). Once the copy has been created, any interaction with it is reproduced to scale on the initial model. In 2015, Oda et al. took up a similar method for exchanging real-time visual manipulations during remote assistance for maintenance procedures (Oda et al., 2015).

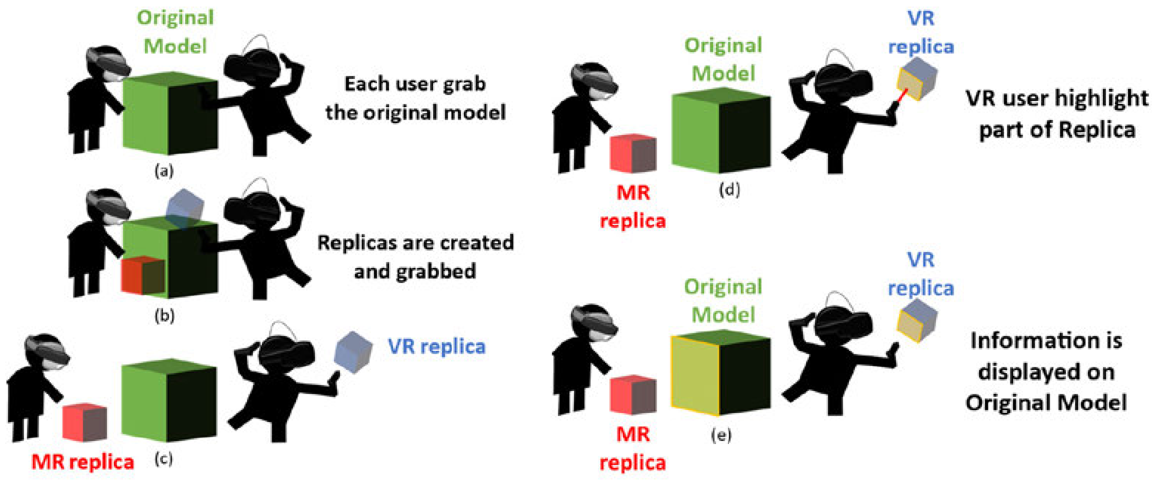

Fig. 2: Schematic representation of our *Replica* interaction system

Our interaction system is based on the same principle: while performing a direct interaction with the shared 3D model (Fig. 2 a), each client creates a *Replica* of the 3D model (Fig. 2 b). This *Replica* can be moved independently from the shared model (Fig. 2 c). Interactions (modified elements, annotations, colour changed…) carried out on the client's *Replica* are specific to it, thus only its owner can see them (Fig. 2 d). If the client wants to share his modifications, he or she needs to *Synchronize* his *Replica* with the shared 3D model, as shown in Fig. 3 (green arrows). Once the synchronization is asked, the modifications of the client's *Replica* are applied to the shared model (Fig. 2 e). If any annotation had already been added to the shared model, these are retained. If the shared model has already been modified and the request is made by the client identified as the *Expert*, its modification takes precedence.

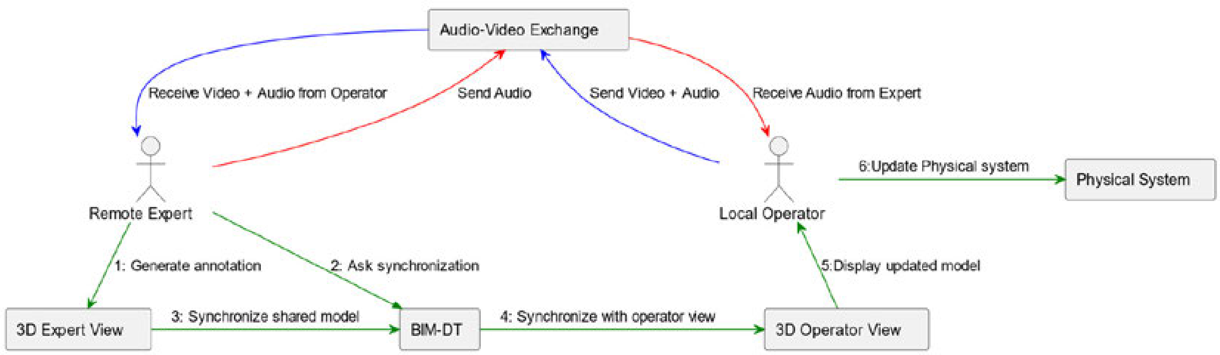

Fig. 3: Representation of the interaction with the *Replica* (green) and the audio-video communication (blue & red)

This method allows both clients to assess different modifications or add several annotations at once before sharing them with the other. It can also allow the client to check the information before sending it, thus avoiding the transmission of incorrect information. If the 3D representation is the digital representation of a Digital Twin, this method also allows both clients to use the DT's simulation engine to observe the impact that a simulated event, such as specific manipulations, can have on the system.

3. USER STUDY

To evaluate our solution, we conducted a user study. Its major purpose is to evaluate the usability of our solution and the impact of the collaboration experience on the performance and resolution time on the *Operator* side. We have decided to make a comparison between two conditions: One using a standard audio-video call, called *Tablet* condition; the other using the MR client of our solution, called *HMD* condition.

3.1 Experimental protocol

A total of 41 participants took part in the study, 12 women and 29 men. They were primarily students and teachers at our school. Participants were asked to sign up using an online form. Only participants with no prior knowledge of the machine were considered. Participants were arbitrarily assigned to one of the two conditions. A presentation of the experiment has been performed prior to commencing the session. For the *Tablet condition*, the *Operator* is invited to use a tablet Samsung Galaxy Tab A. The audio-video call is made via the Teams application (Microsoft, n.d.-b), through the use of a unique account. It has been decided not to use earphones or headphones during the call to simulate an on-site situation, in which the use of this type of device can be difficult due to hearing protection. For the *HMD* condition, the *Operator* is provided with the MR client of our solution. A 5-minute training is performed by the participants to familiarize themselves with the gesture recognition interaction system of the device. Prior to the experiment, to avoid any bias due to a lack of knowledge of the system, it has been decided that the *Expert* would be embodied by a unique actor. The *Expert* is already trained in the use of the VR client, which avoid any issue due to a misunderstanding of the client interaction system.

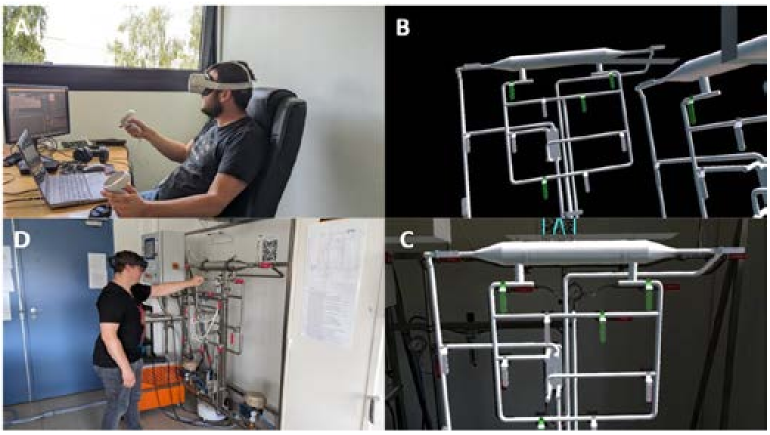

Fig. 4: The *Expert* (a) is moving the valve *2V4* to the *Operator* on his *Replica* (b). The model is synchronized to show the information to the *Operator* (c). The *Operator* can then move the right valve (d).

The *Expert* is provided with a unique inspection plan for both conditions. In the *Tablet* condition, the *Expert* provides vocal instructions to guide the *Operator* to locate the objects he is required to interact with, through detailing the relationships between them. This method proved to be more effective than using visual context (Teo et al., 2019). In the *HMD* condition, the *Expert* use both vocal guidance and the *Replica* paradigm to provide information to the *Operator*, as seen in Fig. 4. During the task performance, the video communication and the participants view were recorded using the in-built system of the device used (record system of Teams for the tablet condition, record system of Windows Device Portal for the MR condition (Karl-Bridge-Microsoft, 2023)).

3.2 Tasks

The scenario simulates an issue with the hot water delivery temperature obtained by the heat exchanger (see Fig. 5). The system is composed of fourteen valves and two different heat exchangers: a shell-and-tube heat exchanger and a plate heat exchanger. This system was chosen for its versatility, as heat exchangers are often found in buildings (HVAC, plumbing systems…). In both conditions, the *Operator* is asked to call an *Expert* to help him identify the issue with the exchanger. Tasks include handling specific valves to alternate between a shell-and-tube heat exchanger and a plate heat exchanger, and to alternate between parallel-flow and counter-flow current, to change the efficiency of the heat exchange. The scenario used by the *Expert* is divided into two parts: *Inspect the system* and *Initial State*. Each part is divided in both *Manipulation* blocks, where the *Operator* is expected to interact with the system, and *No manipulation* blocks, where the *Operator* is invited to give specific information to the *Expert* through descriptions. The *Manipulation* blocks are divided into two types: "*1-handed*" and "*2-handed*" tasks. In the *1-handed* tasks, four operations must be performed, using one hand. In the *2-handed* tasks, only two operations must be performed, but these tasks required to use both hands. Fig. 4 shows an example of interaction in the MR condition. The *Expert* uses the *Replica* paradigm to indicate the correct valve to handle (see Fig. 4 (a) & (b)). Once the valve highlighted, the *Expert* synchronize the system to update the shared 3D model and shows the information to the *Operator* (see Fig. 4 (c)). Then, the *Operator* can move the correct valve (see Fig. 4 (d)).

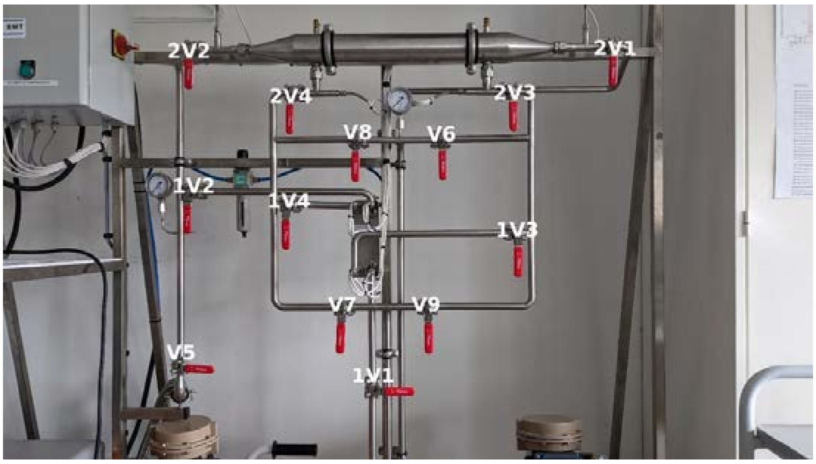

Fig. 5: Physical twin of the heat exchanger with names of the valves.

After completing the *Inspect the system* part, the *Operator* is asked to inform the *Expert* of the hot water outlet temperature obtained. Once the *Expert* has explained the reason for the system's temperature issue and what should be done to correct it, the *Operator* is asked to return the system to its initial state. In this part, the *Expert* can change the order in which the valves are handled in the "*1-handed*" blocks, to avoid a repetition bias with the first part. After completing the *Initial State* part, the *Expert* summarizes the operations conducted by the *Operator* and the conclusion of their common inspection. Then, the *Operator* is invited to end the call with the *Expert*.

3.3 Hypotheses and metrics

In this user study, we stated the following hypotheses:

H_1: The performance time from the completion of the collaborative inspection is faster in the *HMD* condition.
H_2: The number of errors is lower in the *HMD* condition.

To verify our hypotheses, we have used specific metrics. Audio and video of the *Operator* viewpoint were recorded during each experiment for subsequent analysis of the interaction. A timer is started by the test conductor on the *Operator* side at the beginning of the call. For each task, breakpoints are recorded. Errors are also recorded whenever a wrong valve is identified or handled by the *Operator*.

4. RESULTS

Prior to the analysis of the results, we have decided to exclude two participants. One for the *Tablet* condition, where the participant spent most of the experimenting commenting on the relevance of the explanations given by the *Expert*, and one for the *HMD* condition, where the participant had difficulties understanding the purpose of the instructions given by the expert. The following results are thus obtained from 19 participants for the *Tablet* condition, and 20 participants for the *HMD* condition. We performed Shapiro-Wilk (SW) tests on all measurements. For the results non-normally distributed, we performed Mann-Whitney-Wilcoxon (MWW) test on all measurements. For the results normally distributed, we performed a one-way ANOVA test to compare the mean of the samples.

4.1 Completion time

We measure performance time required to complete each experiment. Once the analysis of the overall performance time of the experiment has been analysed, we carry out a detailed analysis of performance times for *1-handed* and *2-handed* manipulations, as well as for phases of the experiment where only vocal instructions were given by the *Expert* to the *Operator* on both conditions.

4.1.1 Global observations

Fig. 6 shows that there is a clear difference in completion time in seconds between the two conditions. The SW test shows that both the *Tablet* condition (W=0.98, p-value=0.96) and the *HMD* condition (W=0.94, p-value=0.267) results follow a normal distribution. For the *Tablet* condition, participants took an average of 763.65 seconds to complete the experiment (SD=76.80). The participants of the *HMD* condition only took an average of 623.55 seconds to complete the experiment (SD=67.70). Because they follow a normal distribution, we use a one-way ANOVA to compare the results. The tests shows that the participants in the *HMD* condition were significantly faster than those in the *Tablet* condition (F (1,37) = 36.6, $p\text{-}value < 10^{-6}$).

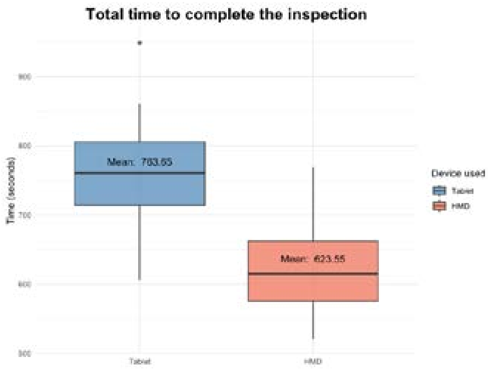

Fig. 6: Total performance time for *Tablet* condition and for *HMD* condition

4.1.2 By task (*1-handed* vs *2-handed*)

Manipulation blocks are divided into two types of tasks. Fig. 7 (a) shows the time difference in seconds between both conditions for the *1-handed* tasks. Neither condition follows a normal distribution (*Tablet*: W=0.9, p-value=0.03; *HMD*: W=0.9, p-value=0.02). The *Tablet* participants spent an average of 193.26 seconds (SD=55.8) to identify and manipulate the valves, while the *HMD* participants only spent an average of 146.43 seconds (SD=26.4). A MWW test is performed and shows that participants using the *HMD* condition were significantly faster than the ones using the *Tablet* condition (W=45, $p\text{-}value < 10^{-4}$).

Fig. 7 (b) shows the time difference between the *Tablet* condition and the *HMD* condition for the *2-handed* tasks. The *Tablet* condition follows a normal distribution (W=0.9, p-value=0.06) for an average time spent of 146.7 seconds (SD=36.1). The *HMD* condition follows a non-normal distribution (W=0.9, p-value=0.01) for an average time of 105.86 seconds (SD=28.4). Thus, we perform a MWW which shows that the *HMD* condition is also faster than the *Tablet* condition (W=49, $p\text{-}value < 10^{-4}$) when the *Operator* should use both his hands to interact with the physical system.

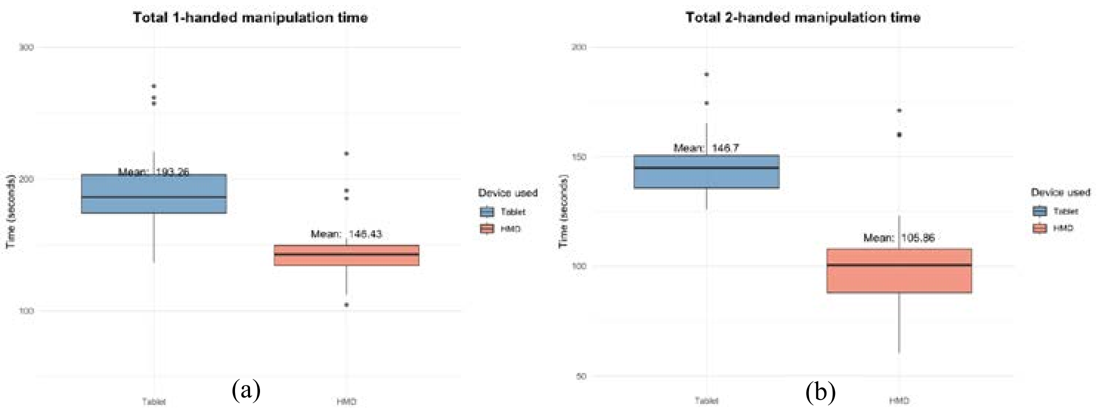

Fig. 7: Total time spent for (a) *1-handed* and (b) *2-handed* manipulation.

4.2 Errors

During the experiment, several types of error have been recorded. A *Simple* error is considered when the *Operator* make an incorrect identification of a valve indicated by the *Expert*, and a *Critical* error is considered when the *Operator* manipulate the incorrect valve. A *Repetition* error is considered when the *Operator* asks for the *Expert* to repeat the information already given. *Simple* and *Repetition* are only considered as one error, while a *Critical* error is considered as two errors, because considered the ones that can worsen the state of the system if performed. Table 1 summarizes these errors and their ponderation.

Table 1: Total and average number of errors for each condition per error type.

Type of errors	Total number for *Tablet*	Average number for *Tablet*	Total number for *HMD*	Average number for *HMD*
Simple (x1)	49	2.45	3	0.15
Critical (x2)	6	0.3	1	0.05
Repetition (x1)	3	0.15	0	0
Total with ponderation	64	2.9	5	0.2

Table 1 shows a difference between the two conditions in terms of errors (58 total errors for *Tablet* condition (Average=3.37; SD=3.02) vs 4 total errors for *HMD* condition (Average=0.25; SD=0.64)). The SW test confirmed that neither condition follows a normal distribution (*Tablet*: W=0.9, p-value<0.03; *HMD*: W=0.4, p-value$<10^{-7}$), thus allowing us to perform a MWW test. The result confirms that there is a significant difference between the total number of errors for both conditions (W=277, *p-value* $<10^{-5}$).

In the *Manipulation* blocks, the *Operator* was invited to use only one or both of his hands to manipulate the valves. Table 2 shows the total and average number of errors in *1-handed* and *2-handed* operations. For the *1-handed* operations, we observe that the *Tablet* condition has a mean of 2.21 errors per participant (SD=2.80), while the *HMD* has a mean of only 0.05 (SD=0.23). A SW test performed on both conditions shows that neither follow a normal distribution (*Tablet:* W=0.8, p-value$<10^{-3}$; *HMD:* W=0.3, p-value$<10^{-8}$). Thus, we perform a MWW test that shows that there is significantly less errors performed on the *HMD* condition (W=314; *p-value* $< 10^{-4}$).

For the *2-handed* operations, the *Tablet* condition has a mean of 1.16 errors per participant (SD=1.21) while the *HMD* condition has a mean of only 0.2 (SD=0.523). As for the *1-handed* manipulations, neither condition follows a normal distribution (*Tablet*: W=0.8, p-value $< 10^{-2}$; *HMD*: W=0.4, p-value$<10^{-6}$). Then, we perform a MWW test to confirm that there is significantly less errors for the *2-handed* operations from the *HMD* participants (W=279, *p-value*$<10^{-2}$).

Table 2: Total and average number of errors for *1-handed* and *2-handed* operations per condition.

Condition	Total number for *1-handed*	Average number for *1-handed*	Total number for *2-handed*	Average number for *2-handed*
Tablet	42	2.21	22	1.16
HMD	1	0.05	4	0.2

5. DISCUSSION

The overall results (Fig. 1) demonstrate a significant difference in performance time, supporting our first hypothesis (H_1). In comparison to the *Tablet* condition, the *HMD* condition is 18,35% faster. We deeply examined both kind of manipulation performed by the participants, *1-handed* and *2-handed* manipulations, separately to establish whether kind of manipulation performance is affected by our solution. We see a significant reduction in the amount of time needed to locate and operate the valves (24,24% for the *1-handed*, 27,84% for the *2-handed*). This reduction can be linked to the obligation to put the tablet down for *2-handed* operations, which may take some time. In the literature, Ladwig et al. found a similar reduction of 30% to locate the correct elements to operate using physical LEDs in comparison with only vocal exchange (Ladwig, 2019).

In a similar way, the effect on the assistance provided to prevent choosing the wrong valve may be observed. Both for the *1-handed* and the *2-handed* manipulations, we see a much-decreased rate of errors in the *HMD* condition (see Table 2). Overall, participants using our solution made 92,58% fewer errors than those using the *Tablet* condition, supporting our second hypothesis (H_2). As shown in Table 1, a more thorough examination of the errors made reveals that there were 93,88 % fewer identification (*Simple*) errors and 83,33 % fewer manipulation (*Critical*) errors. These results are similar to the reduction in errors (89%) observed by Ladwig et al. when using physical LEDs (Ladwig, 2019). Thus, our approach, which uses virtual animations as indicators, makes it possible to avoid misunderstandings and misidentifications during remote support while preventing the need to modify the physical system to support the collaboration.

6. CONCLUSION AND FUTURE WORK

In this paper, we propose a new solution for remote collaboration using a MR client for a local operator and a VR client for a remote expert. This solution aims to help improve remote collaboration during maintenance procedures, using both video communication and 3D models to interact with each other. In our research, we propose a solution allowing both synchronous and asynchronous collaboration using the *Replica* paradigm. We performed a use case to compare our solution with a standard video communication using a video conference program. We stated two main hypotheses that we wanted to investigate about the performance (H_1) and the number of errors (H_2) of the participants.

About the performance time, there was a significant effect of our solution on the total completion time of the participants, hence supporting hypothesis H_1, that the time required to complete the maintenance was decreased by giving the *Operator* contextual visual aids. The fact that *1-handed* manipulations were also quicker proved that our solution has a positive impact on improving the assistance to identify the valves to manipulate, even though the improvement of *2-handed* manipulations was expected due to the free hands provided by the *HMD* condition. In term of identification and manipulation errors, we see a significant reduction for the participants using the MR client. This support hypotheses H_2 that contextual visual aids and using a hands-free device facilitate the *Operator*'s ability to identify and manipulate the equipment they must operate.

In our use case, the *Expert*'s avatar was not on the same height level as the *Operator*. It might be interesting to study the impact that the presence of this avatar might have on the guidance provided by the *Expert*. Some studies have already observed a significant impact of an avatar presence, but without direct interaction of the remote expert with the 3D environment (Piumsomboon, Lee, et al., 2019; Wang et al., 2023).

Furthermore, only the *Operator* side was studied during our use case. It will be necessary to carry out a usability study on the VR client of our solution. The system used for our use case didn't have any usable sensors, so further experiments should be performed to evaluate the simulation model of our BIM-based DT and its impact on the collaboration. The simulation could be used by the *Expert* to perform diagnostic simulations and to test various maintenance operations before guiding the *Operator*, while the *Operator* could use the simulation model on its *Replica* to perform its own diagnostic simulation, and then compare it to the *Expert*'s results.

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CREATION AND ACCEPTANCE OF LOW-THRESHOLD MOBILE TRAINING ON SUSTAINABILITY IN CONSTRUCTION

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ABSTRACT: *Many recent developments in mixed reality applications are exploited for research on improving training in the construction industry. While immersive technologies offer indisputable advantages over classic paper- or multi-media-based training material, access to this kind of technology is still very limited in the academic world and even less widespread in industry. In this paper, the authors follow the current trend of creating low-threshold micro-learning nuggets, which are easily consumable on mobile devices but can be accessed in every web browser. This is essential to reach the construction trade workforces, which for the most part will own a smart or mobile device, but neither specialized equipment, nor will there be time or patience for a lengthy setup phase before learning content consumption. The learning content aims to give construction workers a clear vision of what some of the fundamental components of a sustainable construction site should look like and what role they play in achieving the said vision. The learning content revolves around the initial idea of DGNB certification (German: German Sustainable Building Council), waste management, certification of construction wood, handling of harmful substances and chemicals and some general health and safety regulations that impact the emission of dust, noise and vibration. The paper describes the general approach of the planning, orchestration of learning material, development of the learning nugget, and deployment, as well as a study for acceptance and user experience.*

KEYWORDS: *DGNB, continuous education and training, micro-learning nuggets, responsible consumption and production, smart and mobile devices, sustainable construction, ubiquitous learning, workforce.*

1. INTRODUCTION

The construction industry plays an important part of the European economy, employing over 13 million people (6.6% of the EU employment) (CEDEFOP, 2023). The sector's related effects in other industries are known, for decades, to be extensive as the entire value chain from sourcing over to fabrication and final installation, maintenance and operation, and reuse of products consume enormous amounts of raw materials and energy. As such, 13.5 million other jobs in supplier industries are directly impacted by construction in Europe. In brief, the entire life-cycle chain in the built environment involves, to name a few resources, substantial plant environments, complex products, purposed machinery, and specialized trades with skilled personnel across industry sectors.

While construction is generally seen as a catalyst for stability in economies around the world, it is also viewed in the public perception as one of the most important areas for the green transition, as it is responsible in large amounts for energy consumption contributing to waste and emissions (Teizer and Wandahl, 2022). Yet, in Denmark, the Renovation Wave and the New European Bauhaus, supporting building and infrastructure facilities in the entire of the Europe Union (EU) in becoming smarter and greener, construction significantly contributes to the green transition through large-scale installations of wind farms (EU 2020b). However, Denmark and other countries have realized that sustainable construction plays a significant role in achieving the 30% emission-reduction goal by 2030 and becoming climate neutral by 2050 (DEA, 2023).

While construction remains one of the least digitalized sectors in the EU, new digital technologies will shape it with increasing intensity. Demand for highly qualified workers is growing steadily, as will the skill needs for medium- to low-skilled occupations to learn and practice sustainable goals (UN 2023b). Job surveys, conducted for example by CEDFOP (2023), highlighted substantial training needs for construction workers. Many workers' skills are not well-utilized, which is especially true of construction's significant migrant workforce. Yet, new and far more complex rules and regulations in the built environment demanding ever stricter compliance of construction materials or products, or their integration into installation and maintenance processes, make it even more challenging for the workforce to keep up with state-of-the-art knowledge and practices. All reasons above call for additional learning tools that can create or attract and retain skilled and tech-savvy personnel.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Mario Wolf, Jochen Teizer, *Creation and Acceptance of Low-Threshold Mobile Training on Sustainability in Construction*, pp. 34-45, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.04

The following research questions indicate the objectives of this paper:

- While policy makers often force change through top-down approaches, what bottom-up initiatives can be taken to stimulate change by sustainable behavior?
- Who are the suitable recipients and what are the key focus areas of learning sustainable goals?
- How can awareness among the construction and real estate sector's workforce be created with a tool that is simply to use and still actively engaging them in a learning exercise?

2. BACKGROUND

2.1 Policies on climate forcers

The construction and real estate sector is one of the main sources of emissions globally. Typical new construction and renovation processes use various types of equipment, numerous sophisticated raw material or product resources, and a workforce that is highly specialized in their trade discipline. Yet, combined use in inefficient and wasteful building or operation processes, contributes significantly to different forms of waste and pollution, and irreversible consumption of quite significant amounts of energy (Andrade and Teizer, 2023). In the European Union (EU) alone, the sector is responsible for over 35% of the EU's total waste generation and an estimated 5-12% of total Greenhouse Gas emissions (EC, 2022). On a global mission, according to DGNB (2023), a German non-for-profit organization named "Deutsche Gesellschaft für Nachhaltiges Bauen e.V." (English: German Sustainable Building Council), there is further potential for action in the construction and real estate sector as it is also responsible for:

- 30% of worldwide resources consumption,
- 40% of worldwide energy consumption, and
- More than 30% of worldwide carbon emissions.

Consequently, the urgent need for greener construction is being addressed by several world climate agendas such as the European Green Deal, which aims for climate neutrality by 2050 through the green and digital transformation of EU sectors (EC, 2020a).

2.2 Practices in the construction and real estate sector

Three selected examples from Europe, Germany and Denmark point to the significance of the problem and show that the potential impact of bottom-up approaches, for instance, e-learning tools, can be high.

Example from Europe: According to official reports, only 11% of the existing building stock in European Union undergoes some level of renovation each year (EC, 2020b). However, very rarely (1%, weighted annual energy renovation rate) do building renovation works address the energy performance of buildings, and worse, only 0.2% of building renovation projects reduce their energy consumption by 60%. At this pace, the report concludes that "cutting carbon emissions from the building sector to net-zero would require centuries." It is time to act.

Example from Denmark: Avoiding wasteful and energy-consuming construction, less than 3% of the Danish building stock is built newly on an annual basis. The vast majority of Danish projects in the built environment are already renovation efforts to make its buildings more sustainable. Moreover, most of its existing building stock has reached the age for renovation: Over 80% was built before 1990 and over 75% of the total floor area can be attributed to residential buildings (Statisics Denmark, 2019; Wittchen and Kragh, 2016). Additionally, Danish society, and presumably societies around the world, is becoming more and more aware of the negative environmental impact of our living environments. Almost 50% of the annual energy consumption (Nordic Energy Research, 2023) and nearly 12% of annual CO2-emissions can be attributed to households (Statistics Denmark, 2023). By far, the majority of energy usage in a building takes place during its operational lifetime. In this combination lies a vast challenge how can we improve the performance of our building stock on a scale that meets the now urgent and strict energy requirements?

Example from Germany: Construction and demolition in Germany in 2017 caused 220 million tons of waste, 53% of all industry sectors' combined waste (SB, 2023). A fraction of the waste, while its raw material components are valued highly, is typically recycled (Circle Economy, 2022). Note, while this number includes the demolition of bulk material in road infrastructure, the principles of circularity in the construction and real estate sector yet have to arrive in full swing. Subsequently, as part of the Sustainable Development Goals (SDG 12) (UN, 2023), the sector can benefit from responsible consumption and production. The proposed learning tool addresses some of these goals, see italic text:

- *Sustainable management of natural resources, recycling and reuse*
- *Waste reduction*
- *Avoidance of hazardous substances to air, water and soil*
- *Reuse of components*
- Design for disassembly
- Use of natural resources
- *Awareness for sustainable development*

2.3 Sustainability certificates and target group

While the World Green Building Council has many initiatives around the world, for example, LEED and Green Star, DGNB was founded in 2007 and is Europe's biggest network for achieving sustainable buildings. It is a non-profit organization (NGO) that aims to identify and promote solutions for the planning, execution and use of buildings and communities in order to achieve a sustainable future (DGNB, 2020). Pooling and sharing knowledge, translating sustainability into practice, and sensitizing the general public are its key objectives. As of February 26, 2020, DGNB has more than 2100 members that are comprised of 20% architects/planners, 16% engineers, 21% manufacturers, 17% others, 10% project managers/consultants, 9% investors/developers, and 7% building contractors (DGNB, 2020). DGNB, like the other initiatives mentioned, offers expensive certification courses for a wide range of users, incl. practitioners, consultants, and even students.

The representation of the building contractors in DGNB, and moreover, the large number of personnel it employs, including but not limited to laborers and site superintendents, and supposed to be more than any of DGNB's membership, would be the ideal and predominant use group of the proposed learning tool. In Europe, the construction sector as a share of total employment in the European Economic Area varies by country between 4-10% (Statista, 2023).

2.4 E-learning-content creation in construction and engineering pedagogy

The previous sections have shown, policy and practice differ widely. While behavioral change is one approach to create awareness, yet, hardly any learning tools exist that actively engage the personnel at the workplace. While many methods exist to engage the construction workforce with learning (Wolf et al., 2022), *E-learning (EL),* defined as conducting learning via electronic media, typically on the Internet, depends on the self-motivation of individuals to study effectively.

In the context to construction applications, the effectiveness of EL has been widely studied in safety training and construction management (Lee et al., 2014). Ho and Dzeng (2010) reported a positive impact on Taiwanese labor. Bokor and Hajdu (2014) focused in creating interactive content, incl. use of videos, to facilitate better understanding. Likewise, Lu et al. (2023) investigated the learning curves of participants in modular construction. Kim and Santiago (2005) focused on the instructional development process through the impact of educational technology. Clevenger and Ozbek (2013) and El-Adaway et al. (2014) both addressed service-learning concerning evaluating sustainability competences in the engineering curricula. However, their work made not much use of EL. Similarly did Love et al. (2015), while examining collective learning by coaching, not focus on sophisticated technical aids.

A few other teaching methods are reviewed rather in brief to let readers understand the differences what they offer:

- *Game-based learning (GBL)* is where game characteristics and principles are embedded within learning activities that reward and motivate the participant to think critically. In construction, Oo et al. (2016) focused a game on cost estimation and bidding and Sacks et al. (2007) on reducing waste in construction by applying lean principles. Teizer et al. (2020) utilized Internet of Things (IoT) technology in a serious game for the purpose of identifying and eliminating waste during the construction operations. Jacobsen et al. (2021) extended their work to multi-user GBL-experience in Virtual Reality (VR). Few studies exist to GBL with regards to sustainable design and LEED or equivalent concepts; Dib et al. (2012) is one of these. However, Dib et al. (2013), Ayer et al. (2016), Castronova et al.'s study (2017), Dancz et al. (2017), Clark et al. (2021), most of the studies use university students for evaluation. A late criticism, practitioners should be used instead, was raised by Adami et al. (2023).
- *Problem-based learning (PBL)* uses complex real-world problems as a vehicle to promote student learning of concepts and principles as opposed to direct presentation of facts and concepts. It stimulates

finding and evaluating research materials, critical thinking skills, problem-solving abilities, and communication skills. PBL is often practiced in the format of groups, as seen in architectural studios and construction management courses at universities (Williams and Pender, 2002), and life-long learning workshop exercises or seminar series in industry (Duch et al, 2001).

- *Mobile learning (ML)* is education or training conducted by means of portable computing devices such as smartphones or tablet computers. Among studies investigating m-learning technology acceptance (Al-Rahmi et al., 2021), Wolf et al. (2023) investigated construction product quality by utilizing mobile Augmented Reality (AR) technology.
- *Life-long learning (LLL)* is a formal or informal approach to personal or professional learning that is continuous and self-motivated. Froehle et al. (2022) studied civil engineering skills development in LL using semi-structured interviews. Gao et al. (2022) explored the drivers and barriers of LL in construction, Salajan and Roumell (2021) outlined a holistic view of LL for European learning opportunities and promoted clearer links across educational pathways and sectors, incl.
- *Micro-learning and Nuggets (MLN)* focus on learning by creating concise and bite-sized chunks of information. Nugget learning is a subset of micro-learning that focuses on the development of personal nuggets or mini-lessons at the end of each unit (Ploder et al., 2021). While recent research focuses on the emergence of technology for MLN and how it can perfectly address the next-generation workforce's learning needs (Nanjappa et al., 2022), delivery of MLN in the context of construction applications, including sustainability, has yet to be explored in greater detail.

Several other studies in the architecture and civil engineering domain focused on the effectiveness of education, for example, Vorster (2010) and Mostafavi et al. (2013). Yet, they fall short in explaining the role of advanced technology in education and training. These limitations indicate a vast, and still unexplored, opportunity for leveraging technology in learning, as recently shown by Wang et al. (2020) and Wolf et al. (2022).

3. METHODOLOGY

Based on the concepts and related work mentioned in the background section, the methodology section introduces the exact goals and requirements for the training application, was well as the theory behind both the learning and gamification content. Figure 1 shows the general approach, which is derived from the common SCRUM practice in software or product development.

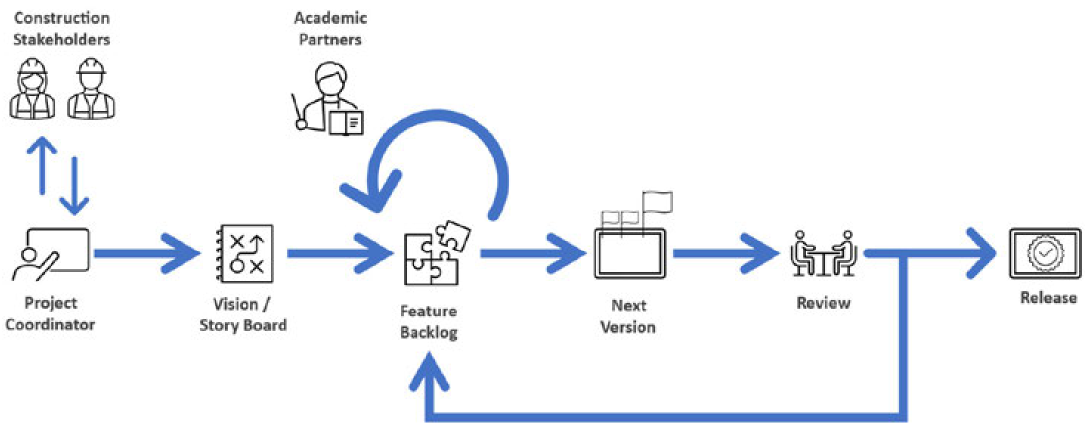


Fig. 1: Development approach for the training application.

The motivation for the training application is based on the needs of stakeholders from the Danish construction sector. A central project coordinator assures the alignment of goals and requirements, as well as providing the solution to the stakeholders after the development. The vision and storyboard are developed with the academic partners after which the iterative development itself starts. A feature backlog is derived from the story board, with each feature being developed as a singular entity. Once enough features are finished, the next version of the training application is released for review with the project coordinator, who keeps contact with the construction sector stakeholders. This loop is repeated until the feature backlog is empty so that every feature from the vision is implemented to sufficient standards. After that, die release version of the application is compiled and provided to the project coordinator.

3.1 Goals and requirements

The goal is to create a learning application that is easily consumable on mobile devices but can be accessed in every web browser if need be. Due to the ubiquitous availability of smart mobile devices and the ease of use of scanning i.e. QR codes, the mobile view is the favorable focus. The target audience is construction workers with basic training and at least prior experience regarding waste sorting on a construction site.

The requirements were to create a fun training, uses gamification elements and transports some core rules for sustainable construction. The five main talking points are: Waste sorting on the construction site, certified wood use, handling of hazardous substances, health and safety regarding dust, noise and vibration exposure and the reduction of energy consumption. The story-board for the training was developed in a virtual whiteboard by both construction experts and academic staff in an evolutionary manner, iterating ideation, creation and feedback for each section after the initial story development. There is no integration into an existing Learning Management System, no user management or login required to use the training, no persistent data storage, especially not on personal information and the final product should be hosted on any regular webserver without special setup.

3.2 Content and structure

The learning content itself is very limited in this context, as the target audience should have prior knowledge in most fields touched upon in this training. It is assumed that the training acts more like a refresher of that long-term knowledge and a reminder of the importance of the acts of each individual.

To minimize the time needed to read texts on the smart device, each section is introduced by an animated character video-narrated by a voice actor. The following take-away messages and key points were chosen for the training.

3.2.1 Introduction

Awareness for the impact of the way most industrialized nations work is one of the main goals of this training application. The introduction therefore lays the foundation by stating that, if scaling Denmark's energy and resource consumption up to the world population, the world's yearly available raw resources would be consumed 420%, or within weeks instead of a full year. Therefore, the goal is to become generally better at reusing, recycling, and recovering, in order to reduce the consumption of raw materials, in this case in the construction sector specifically. As stated earlier, the DGNB certification is a comprehensive tool that creates guidelines for a building's environmental, economic, social, and technical quality. Many clients are demanding DGNB-certificated buildings and it is therefore important that craftsmen not only follow those guidelines but understand their impact. Therefore, the introduction offers a perspective of what can be done in everyday life on the construction site.

3.2.2 Waste sorting

Denmark's goal for 2030 is to re-use, recycle and/or recover a minimum of 70% (weight percent) of raw waste materials. In order to reach this goal, there is a need to ensure efficient and correct material sorting on the construction site. With efficient sorting and reuse, the reduction of the currently excessive consumption is more easily achieved. While providing some background with the animated character videos, the waste sorting section should offer an active exercise in waste sorting as depicted in Figure 2. While most sorting tasks of raw materials seem obvious (metal into the metal container, wood into the wood container, etc.), the edge cases are the important ones to reduce waste and/or problems further down the recycling path. For example, metal buckets with leftover paint belong in the correct waste bin for harmful chemicals, wet sheetrock can not be recycled easily and should be separated from dry sheetrock and reinforced concrete belongs to regular concrete and not to general metal.

3.2.3 Certified wood

For valid certification of a building, every raw material has to be certified too. It is up to the craftsmen to validate those certifications on the material that arrives at the construction site. For the wood sector, Denmark generally uses two internationally recognized systems for FCK and PS3 from forests with Skovbo for the benefit of present and future generations. This quiz offered in this section should put the user into the perspective of a worker tasked with receiving a batch of wood. Before signing the delivery note, the user must identify the correct certification marks or decline the delivery completely. This step in particular is quite harsh in reality and awareness of the importance of correct certification needs to be established as the "higher goal" instead of "just keep working, it's just wood".

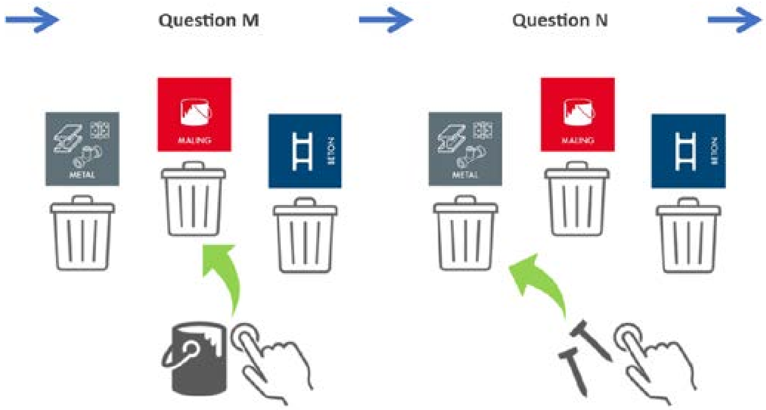


Fig. 2: Sktech of a dragg and drop quiz for waste sorting.

3.2.4 Hazardous substances

While there is great value in being able to reuse materials, if the materials used on the construction site contain chemicals, they usually cannot be used in other contexts where health factors play a greater role. Awareness of the most common harmful substances is essential, as well as which substances are suitable for use on the sustainable construction site. There is a considerable number of valid certifications that can be found on the chemical's containers and, once again, need to be recognized by the skilled craftsmen. The quiz in this section demands the user to judge the sustainability of certain chemicals, like paint for example, based on the packaging and once again to decide whether to accept or decline its use on the construction site.

3.2.5 Dust, noise and vibration

Health and safety play a major role on the construction site. Sustainability also encompasses a safe working environment and the awareness for dangers is one of the most crucial factors in preventing accidents. Especially the awareness of the accumulating severity of seemingly minor hazards like exposure to dust, noise, and vibration are put into focus in this section. Not only is the protection relevant for the workers conducting the operations but also for their coworkers and the surrounding neighborhood. The importance of reducing the noise, dust, and vibration at the source as much as possible and the awareness of restrictions regarding how much and when workers are allowed to apply the mentioned procedures are mediated with easy-to-follow videos and examples.

3.2.6 Energy consumption

Energy consumption is a key metric in every sustainability initiative. In the future, the EU taxonomy will include technical audit criteria for a wide range of activities related to energy supply and consumption on- and off-site construction. It is therefore important that craftsmen prepare for their future tasks, especially since more equipment and machines, incl. hand-held power tools become electric and battery-powered. Likewise, fossil fuel consumption is to be reduced, for example, idling vehicles present a significant waste and contribute to poor productivity. Moreover, excessive energy use to heat temporary office containers plays a critical role during late fall, entire winter, and early spring times, and as such, does cooling during summer times. Lighting of the construction site to ensure sufficiently safe walking pathways and workplaces, or providing a pleasant work desk atmosphere also contribute to energy consumption. While the implementation of Light Emitting Diodes (LED) have substantially reduced the energy needs, yet not all construction sites make use of it, and those who do, can either optimize their use and may at least need to become familiar with the appropriate recycling guidelines.

4. IMPLEMENTATION

In the following paragraph, the tools used to create the low-threshold training are presented, followed by the detailed description of the created content. The main editor for the created training is Microsoft PowerPoint 365, which is enhanced by the use of an E-Learning content management addon called iSpring Max. The latter allows the creation of interactive content and the compilation of the final product into HTML5 plus JavaScript, to be consumed with both mobile devices and PCs. The training could also be compiled into a so-called SCORM (Sharable Content Object Reference Model) package, so that it may be imported into regular learning management systems (LMS) as a separate activity in a more extensive learning path or e-learning course. When deployed as

HTML5, the hosting is identical to any static website, meaning a regular webserver will suffice for hosting and displaying the training.

For media creation, the assortment of applications of the Adobe Creative Cloud were used, most notably the Adobe Character Animator, which allowed the creation of the animated avatar and the voice acting to be conducted separately. The created avatar is depicted in Figure 3, showing some of the animations and the active lip sync.

Fig. 3: The created avatar as used in the Character Animator.

The avatar was chosen based on the stakeholders wishes, but can be switched out very easily if need be, while keeping the animations, triggers and the eye- and body-movement. When switching out the graphical representation, usually, the audio changes too. In that case, the lip-synchronization can be recalculated to match the graphic and audio representations.

Figure 4 gives an overview of the structure and the logic implemented in the training application.

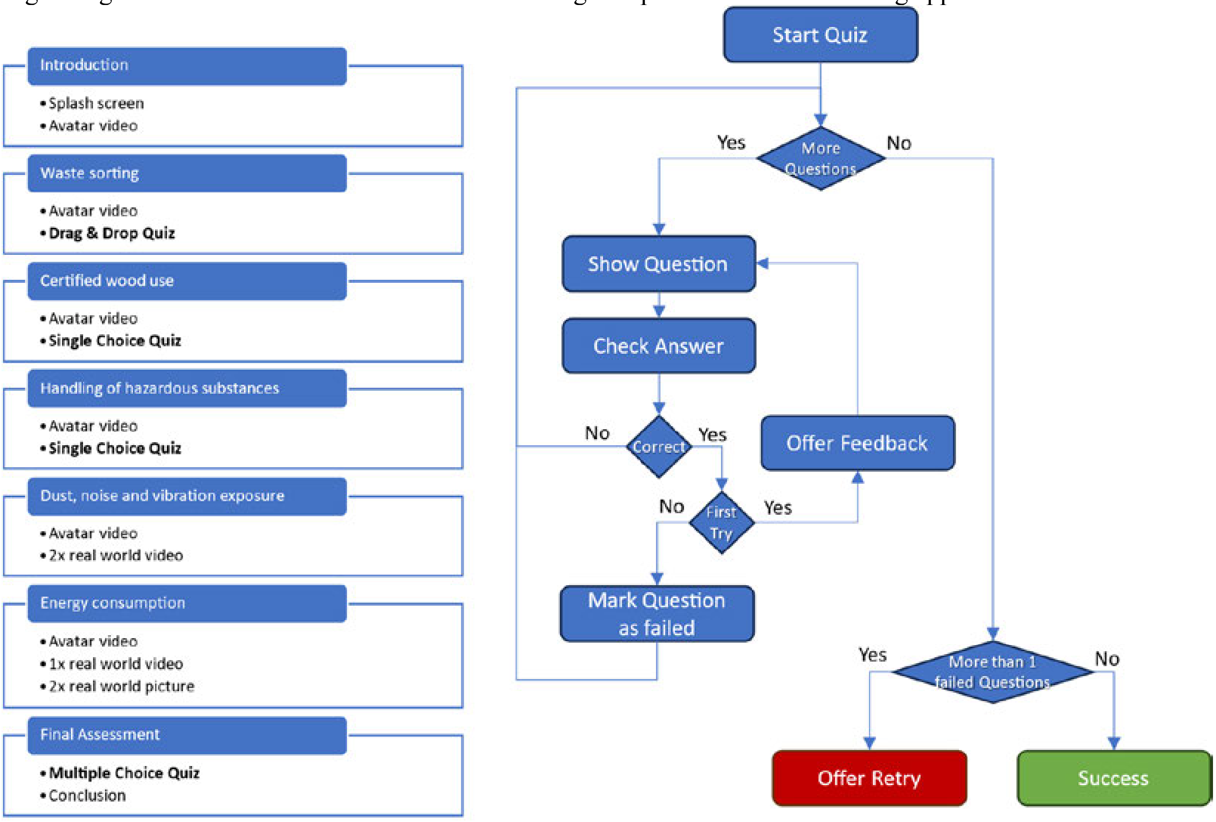
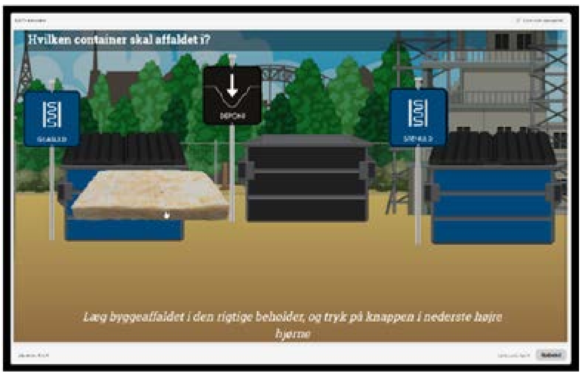


Fig. 4: Structure of the training and implemented quiz logic.

The initial introduction is done with a splash screen, followed by an avatar video. A splash screen is omitted in the sections, as an avatar video represents both the switch to another section, as well as providing background information and an introduction to the topic. Quizzes in the following description are all uniform in their way of providing feedback and explanation right after confirming in the answer and offering a second try, in case the given answer was wrong. After a second wrong answer, the question is marked as not successful. Each quiz only allows a single question to be answered not successfully, with unlimited attempts for each quiz. When finishing a quiz successfully, the next section is unlocked.



(a) Waste.

(b) Certification.

(c) Environment.

(d) Health and safety.

(e) Emissions.

Fig. 5: Training challenges: (a) waste sorting, (b) certified wood, (c) hazardous substances, (d) dust, noise and vibration, and (e) energy consumption.

4.1 Waste sorting

After the avatar video, the trainees are presented with the first quiz (Figure 5a). The quiz focuses the correct assignment of material to recycling bins or containers, with narration at the start of the quiz to clarify task and functionality. There are eight questions in the quiz, which are simply solved by dragging and dropping the waste to the correct bin.

4.2 Certified wood

After the avatar video, the trainees are presented with a real-world video, showing a truck delivering construction wood (Figure 5b). The quiz then revolves around the identification of relevant certifications. Several life-like delivery documents are presented and the trainees must choose to either accept or decline the delivery, based on the provided certification.

4.3 Hazardous substances

After the avatar video, the trainees are presented with the third quiz (Figure 5c). There are six different typical chemicals, which are regularly used on construction sites, and the task is to check for the correct certification.

4.4 Dust, noise and vibration

After the avatar video, the trainees are presented with two real-world videos and instructions with narration regarding health and safety regulations (Figure 5d). As Health and Safety Trainings are regularly conducted, there is no quiz in this section.

4.5 Energy consumption

After the avatar video, the trainees are presented with two real-world videos and instructions with narration regarding health and safety regulations (Figure 5e). As health and safety trainings are regularly conducted, there is no quiz in this section.

4.6 Final

The final of the training is a quiz of four questions with a summary of the training at the end.

5. STUDY AND PRELIMINARY RESULTS

According to studies of Wolf et al. (2022) and Adami et al. (2023) practitioners as participants that evaluate the application matter. While the evaluation of the testing with an initial group of dozen practitioners is pending, preliminary comments that both workers and construction site staff left with the authors indicate that the developed application is technically sound to communicate the relevant content to the participants. The participants claimed to have known most, but not all of the content, thus receiving some value from using the application. While neither personal data about the participants nor IP-addresses of their smart devices accessing the application were collected, completion rate and time spent when navigating within application was recorded. Preliminary data indicates that participants stay within the envisioned time span of less than 15 minutes to complete the application. Abortions before ending the application were very low, probably due to the application still being novel. Yet, few participants mentioned that additional or variations of the examples within each module could help make it more attractive or revisit in the future or as part of continuous training short courses that they also recommended. One participant expects that repetitive use of it "makes some of us [workers] change thoughtless behavior". Yet, the authors recommend the application for extensive testing with structured evaluation methods, utilizing, for example, anonymized pre- and exit surveys and/or interviews, and, perhaps, accompanied by behavioral observations of workers on the construction site. In addition, a verbal review meeting with site management staff who also acted as participants, revealed that demographic developments in the construction industry need to consider as well. While smart and mobile devices offers a communication style that attracts younger workforce and subsequently increases the chance that workers accept to participate, offering multiple international languages prevalent in the target country might be required, especially for migrating workforces that are not familiar with the local language. Likewise, the dependence on a voice actor while listen to the application may require a quiet space or headphones to operate it. Overall, preliminary results demonstrate technical feasibility and the workforce seems to accept the delivery method.

6. CONCLUSION

The tools mentioned in the implementation section allowed for a rather quick implementation of the desired training. While the technical and content goals were met, several quality-of-life requirements, which came up during the implementation process, could not be implemented due to restrictions in the frameworks, applications or time constraints. Most revolved around the exact depiction of feedback in the different quizzes or certain behavior regarding user interaction. Some of the preliminary results to a study showed that technology to create an effective learning nugget for achieving sustainability goals in construction exists. This can be used to counter the general trends in the construction workforce that can be named: significant labor shortage in certain trades, often replenished by migrant personnel, joining construction initially with limited skills or awareness. Future work will encompass the creation of multilingual trainings in the now focused field, as well as the creation of a larger scope training, based on multiple micro-learning nuggets, which will allow more room for learning content, media and assessment of learning outcomes.

7. ACKNOWLEDGEMENT

This research has been funded by Realdania and Industriens Fond under the Danish research project "Bæredygtighedssimulator" of the Rådet for Bæredygtigt Byggeri and ConTech Lab.

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A COLLABORATIVE PLANNING MODEL FOR OFFSITE CONSTRUCTION BASED ON VIRTUAL REALITY AND GAME ENGINES

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ABSTRACT: *Accurate process planning is essential for successfully implementing offsite construction projects. New technologies, such as virtual reality (VR), have been proposed as potential proactive solutions that allow users to experience and train on OSC processes to ensure safety and efficiency in an immersive environment. However, current VR applications in OSC projects (VR-OSC) problems are limited to residential projects and target single phases of the OSC implementation. This study proposes a VR framework to train participants on modular bridge construction processes. The developed model comprises several OSC phases, such as fabrication, transportation, and assembly. Furthermore, the study explores the use of collaborative platforms that can be associated with the VR model to ease the model and the developed scenes. The model is tested on a sample of participants that evaluated the performance of the model and provided areas of improvement. The results showed the capabilities of the model in providing an immersive experience for participants and connecting different phases of the OSC projects. Also, the results show that the experiment length and complex controlling buttons are among the areas of improvement. The developed model is expected to facilitate safe and efficient training for complex OSC projects.*

KEYWORDS: *Offsite Construction, Building Information Modeling, Virtual Reality, Game Engines*

1. INTRODUCTION

As the conventional construction method has been argued to provide less productivity compared to other industries, offsite manufacturing and modularization solutions have been proposed to enhance the efficiency of the construction industry (Alsakka et al., 2023; Hussein et al., 2022). Modular construction, as a part of offsite construction (OSC), is the process of assembling fully finished modules in the factory, transporting them to the job site, and installing them in the correct locations (Assaf et al., 2023). However, the efficient adoption of modular construction requires a high level of information technology and digitalization (Ezzeddine & García de Soto, 2021). Hence, various digital solutions and technologies have been adopted in modular construction methods, including computer vision (Alsakka et al., 2023), blockchain (Wu et al., 2022), Internet of Things (IoT) (Li et al., 2022), and immersive technologies (Zhang et al., 2023).

Virtual reality (VR), as a part of immersive technologies, has been used by many researchers to enhance the implementation of OSC techniques. VR can be defined as a simulation of the real world in which participants can interact with the virtual assets and experience different degrees of immersion in the simulated environment (Abbas et al., 2019; Alrehaili & Al Osman, 2022). These degrees of virtual immersion include non-immersive, semi-immersive, and fully immersive VR models (Zhang & Pan, 2021). The virtual scenes in the simulated environments are usually done using game engines (Olofsson, 2018). Through the use of game engines, the interaction rules and conditions are defined using coding scripts (Kumar et al., 2011). This combination of VR and game engines have been used in several research domains, such as health and therapy treatment (Mevlevioğlu et al., 2022), the food and shopping industry (Gil-López et al., 2023), and the construction industry (Boton, 2018).

As the combination of VR and game engines is a promising approach in many industries, OSC also benefited from it. The VR-OSC research has gained massive attention in recent years. For instance, Zhang and Pan (2021) have proposed a VR model of tower crane location planning for modular construction projects. The model was created using the Unity3D game engine and was supported by a graphical user interface (GUI) to facilitate the selection of crane types, layout plans, and camera views. Similarly, Shringi et al. (2023) aimed to develop a VR model to train operators on crane operations in offsite construction. Their model included a safety index that was calculated based on penalties applied to each of the identified risks in the scene. In safety and ergonomics analysis, Dias Barkokebas et al. (2022) combined a VR model with a motion capture system to evaluate workers' ergonomics in OSC factories. The VR model was developed using Unreal Engine, and the data collected through the motion capture technology was analyzed using rapid entire body assessment (REBA) and rapid upper limb assessment (RULA) methods. Similarly, Joshi et al. (2021) proposed a VR safety training model for precast factories for

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Mohamed Assaf, Rafik Lemouchi, Mohamed Al-Hussein, Xinming Li, *A Collaborative Planning Model for Offsite Construction Based on Virtual Reality and Game Engines,* pp. 46-56, DOI 10.36253/979-12-215-0289-3.05

employees. The model was developed using Unity3D and was used to train the employees on the personal proactive equipment (PPE), stressing processes, and safety measures in the factory. Inyang et al. (2012) developed a VR model to assess safety risks in panelized construction factories. Their model evaluated different layouts of the manufacturing facility, and ergonomic risks were evaluated for each of the selected layouts.

For educational purposes, VR has proven to be an effective tool in educating participants and students on OSC processes (Eiris et al., 2020). For instance, Beh et al. (2022) introduced an educational model to train students on inspection activities of the OSC projects. Game engines were used in their model to develop educational game scenes, including fire inspections, leak inspections, and rain system inspections. Similarly, Sampaio and Viana (2014) created a VR model to educate students on the processes included in the prefabricated bridges. Furthermore, VR-OSC research also targeted the use of VR in evaluating design alternatives and factories/site layouts. For instance, Zhang et al. (2006) have developed a VR model to help participants in evaluating design alternatives in prefabricated construction. Their model assessed many criteria, including production time and cost. Zhang et al. (2021) developed a virtual environment to improve the generated value to the customer in offsite construction facilities. Many other applications of VR-OSC research were found in the literature, including collaborative digital platforms in modular construction projects (Ezzeddine & García de Soto, 2021) and the use of VR in circular economy of OSC projects (O'Grady et al., 2021).

Despite the contribution provided by the previous studies, they lacked the following aspects: 1) all of the mentioned studies have considered the use of VR in OSC residential projects. OSC, especially modular construction, can be employed in many project types, such as bridge construction, which is usually referred to as modular bridges (Lechner et al., 2021). Modular bridge construction includes fabricating heavy steel and concrete modules in manufacturing facilities and shipping them to the bridge to be aligned and installed (Xiangmin & Dewei, 2021); 2) most of the presented studies have tackled the OSC life cycle from a single perspective, such as onsite installation (Zhang & Pan, 2020) and manufacturing phase (Dias Barkokebas & Li, 2021); 3) the developed models have limited accessibility, as the participants needed to be in the lab where the experiment was being held. In light of the mentioned limitations, the current study aims to bridge these limitations by developing a VR model that considers all of the implementation phases of modular bridge construction to train practitioners on different OSC processes and connect various project teams. The objectives of this study can be summarized as follows: 1) review the literature contributions in VR-OSC research; 2) develop a framework of a VR model considering the fabrication, installation, and transportation phases of modular bridge construction; 3) test the developed framework on an actual case study on a modular bridge and gather feedback from participants for improvement; 4) develop a cloud platform to support remote access to the model. The rest of the paper is organized as follows: Section Two summarizes the methodology outline, Section Three discusses the model development in the mentioned phases, Section Four discusses the analysis of the model and provides the areas of improvement, and finally, Section Five concludes the current study.

2. METHODOLOGY SECTION

This section demonstrates the methodology and the tools used in this study. Figure 1 outlines the study framework. As mentioned, the proposed framework aims to provide engaging and efficient training for various OSC processes, improve stakeholders' connectivity and coordination, and assist participants in getting familiar with OSC processes. The proposed framework targets many project teams, such as the factory team, onsite assembly team, and transportation team. The developed model in the game engine is further upgraded to be accessible online for project teams.

The framework combines the merits of BIM modeling and game engines. The framework starts with building a 3D BIM model of the modular bridge construction project. The 3D model was developed based on the statistical system of an example of a modular bridge addressed by Xiangmin and Dewei (2021). Autodesk Revit is used in this step to develop the BIM model. An FBX format is used to export the developed BIM model, with all of the needed information and real dimensions, to the game engine tool. In this study, Unity3D is used as the game engine tool. Unity3D has been used by research scholars in developing serious games and VR scenes due to its efficiency and compatibility with technologies, such as BIM (Zhang & Pan, 2021) and hardware sensors (Jeon & Cai, 2021). After the FBX model is imported to the Unity3D platform, the interactions in the virtual scenes are added using C# programming language. The developed virtual scenes include the following: an exploring scene, a transportation scene, a yard scene, and an onsite scene. The scenes will be further detailed in the following section. To facilitate easy access to the developed VR model and leverage the use of the VR model, web cross reality (WebXR) and Web Graphics Library (WebGL) are used. WebXR facilitates the ability to develop fully immersive virtual models across the web using several types of hardware (Bao et al., 2022). A modular construction case study is also discussed to test the proposed methodology, and participants are then asked to evaluate the designed tool, and the feedback is used to improve the development of the model. The following sections will detail the development of each of the discussed steps.

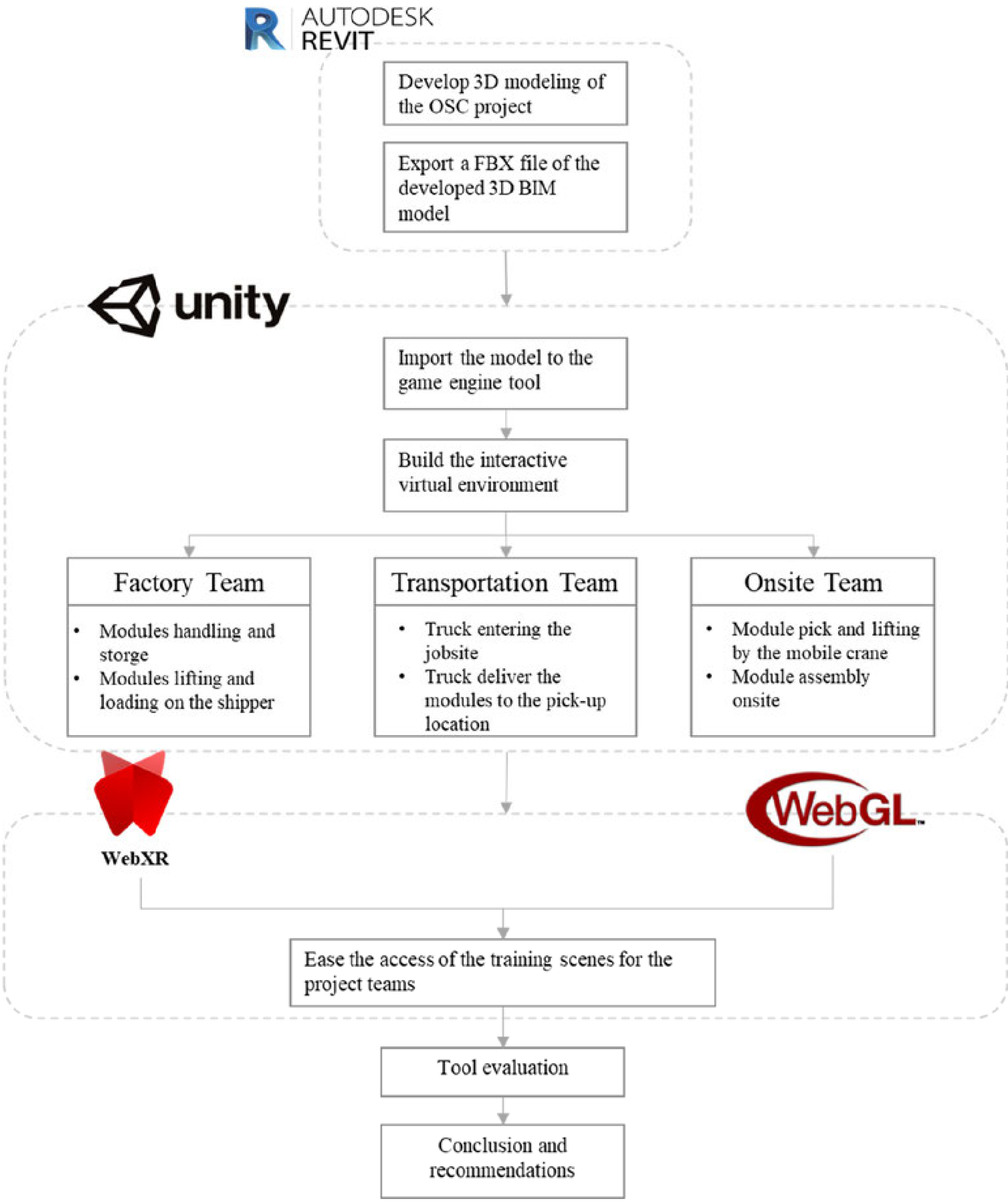

Fig. 1: The study framework

Furthermore, the model testing was performed through two main steps. First, a non-immersive environment is created where the participant can enter any of the developed scenes and test the efficiency of the developed model. This option is valuable when deploying the developed virtual model on the shared cloud. This arrangement allows participants to access the model without the need to have a VR headset and controller. In the second step, the model is then tested in a fully immersive environment. The VR headset and controllers are connected to the virtual model in the Unity3D platform. The controlling buttons are then edited and added to the VR controllers. Participants in the fully immersive model can perform the same tasks using the VR controller. Participants are asked to evaluate the model after the experiment and to provide possible areas of improvement.

Besides the software tools used in the study, a number of hardware tools are also used. The installation of the VR headsets and controllers is shown in Figure 2. The hardware used in this experiment includes the following: 1)

HTC VIVE headset, 2) HTC controllers, and 3) two bases. All of these hardware pieces were connected to the PC and added to the Unity 3D game engine.

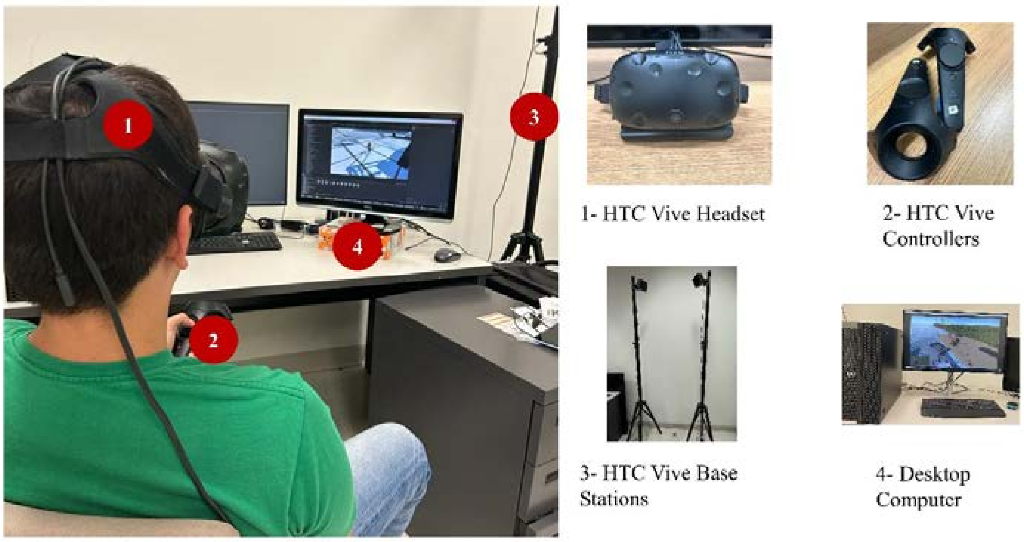

Fig. 2: Hardware used in the VR experience

3. MODEL DEVELOPMENT

In this section, the development of the model is discussed. As mentioned above, Autodesk Revit is used to develop the BIM model, Unity3D is used to develop the virtual interactive scenes, and WebXR is used as the web platform of the model. A case study of a modular bridge is discussed in this section to demonstrate the proposed methodology. It is worth noting that the location, details, and drawings of the case study are remained anonymous.

3.1. BIM model

This section shows the development of the BIM model. The chosen case study comprises the following OSC elements: prefabricated steel modules and precast reinforced concrete slabs. Figure 3 shows the details of the developed BIM model. The shown steel modules are first installed on the bridge, and then the precast slabs are installed on top of the steel modules. The fabrication of the steel modules is beyond the scope of this study. However, handling the steel modules at the factory is included in the developed scenes.

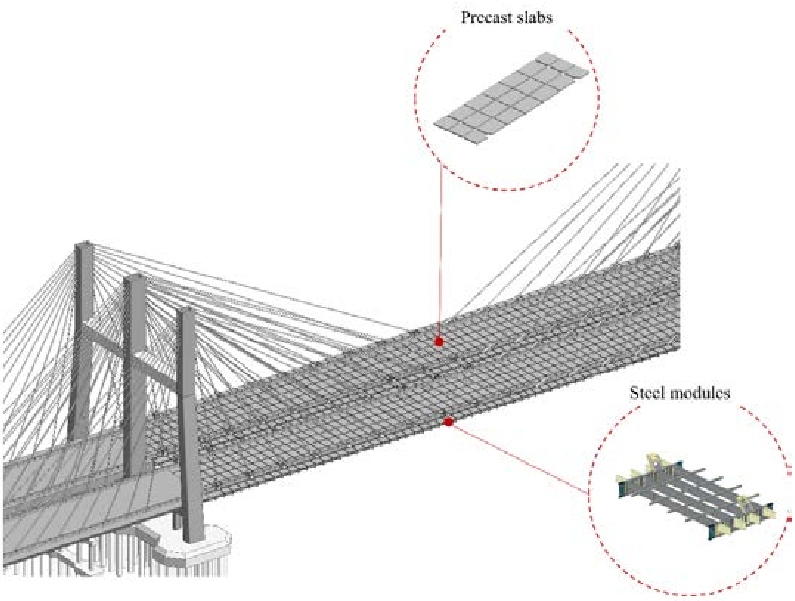

Fig. 3: Developed 3D BIM model.

3.2. Virtual Scenes

This section discusses the development of virtual scenes in this study. The section includes the following scenes: the exploring scene, the yard scene, the onsite scene, and the transportation scene. Further, the graphical user interface (GUI) is used to ease the accessibility of the developed scenes. Figure 4 shows the developed GUI. The user can easily navigate among different choices, including scene selection, scene instructions, and scene options (i.e., audio adjustment).

Fig. 4: GUI of the developed game scenes.

3.2.1. Explore Scene

In the Explore Scene, the participants can walk around the VR model in a fully immersive environment. Figure 5 includes a snapshot of the developed scene. The use of this scene for participants is to get familiar with the project before the actual implementation. In this scene, the location of heavy equipment, material storage, special connections, and safety precautions are included. The participants control a character that moves in the virtual environment to explore the mentioned attributes. Participants can choose different camera views, such as first-person or third-person views. All of the elements in the virtual environment, along with the moving characters, are equipped with colliders, making the experience more realistic. Further, the scene is equipped with sound effects, such as footsteps, to increase the engagement of the participants in the virtual environment.

Fig. 5: Exploring scene of the developed model.

3.2.2. Transportation Scene

This scene includes the transportation of the precast slabs to the pickup point. Figure 6 shows a snapshot of the scene. The scene includes the following: a signaler character to guide the truck, signs for the safe entry of the truck, barriers that separate that truck's movement from other vehicles and elements on the job site, and vehicles moving in opposite directions to make the experience more realistic. Furthermore, the sounds of the moving vehicles are also added to the scene for an engaging experience for the participants. In this scene, participants (in this case, truck operators) are expected to drive the truck from the first location to the pickup location. The truck should be able to lift the slabs and assemble them on top of the steel module in the next scene. The scene also shows the clearance of the truck and surrounding elements. The scene then alerts the participant using a beep sound when the clearance is below a certain value. This is achieved through the physical attributes of the elements and collider functions in Unity3D.

Fig. 6: Snapshot of the transportation scene

3.2.3. Onsite Scene

The onsite scene includes the assembly of precast slabs on the steel module. Figure 7 shows a snapshot of the scene. The scene includes heavy equipment, such as a mobile crane, and heavy vehicles, such as trucks. The scene includes many tasks for the participants, such as moving the mobile crane, manipulating the crane boom, tying the module, lifting the precast element, and assembling. The participant (crane operator in this scene) is expected to install the precast slab in the correct location. To make it easier for the participant, an assistant is provided for accurate precast element installation. For instance, a clearance check algorithm is provided so that the participant would know the distance between the element and the nearest surrounding elements. The participant will be notified when this distance goes below a certain value. Furthermore, participants can also enable an option that assists them with the installation process by indicating the projection area on the below elements.

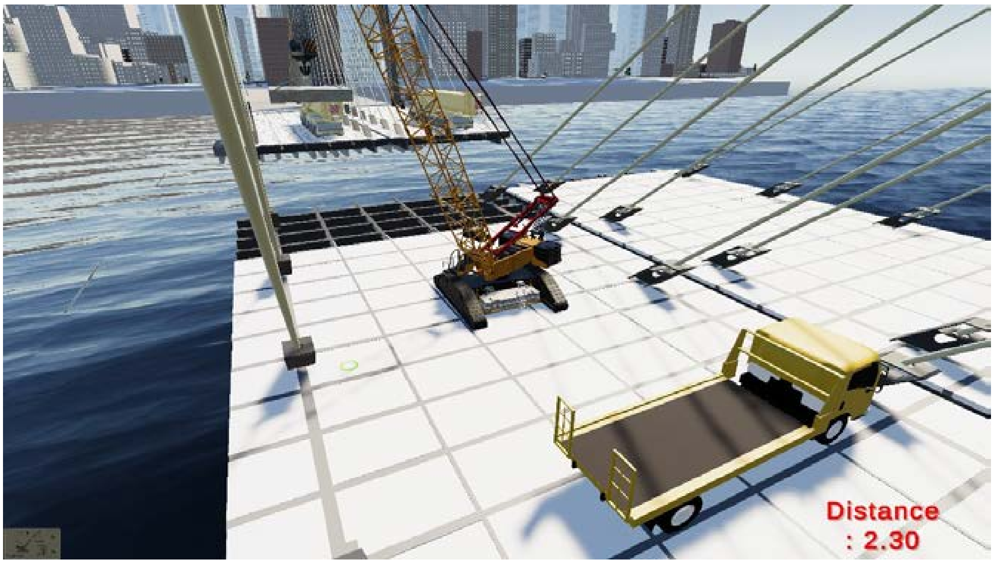

Fig. 7: Snapshot from the onsite scene

3.2.4. Yard Scene

Similar to the onsite scene, this scene targets the handling of the modules in the factory. It is worth noting that in the displayed case study, the factory is represented as a yard where the steel modules were being manufactured. Figure 8 depicts a snapshot of the factory scene. The scene shows how are the steel modules arranged on the yard. The participant is expected to do the same tasks included in the previous scene, but this time with an aim to place the steel module on top of the barge, which later will be shipped to the bridge to be installed. The participant can hook the module and lift it to be aligned on top of the barge. The model provides Various guidelines, such as alerts and the location of the installation. The participant can choose between various points of views, such as the operator view and the barge view. Sounds of the crane engines are also provided to engage the participants in the experiment.

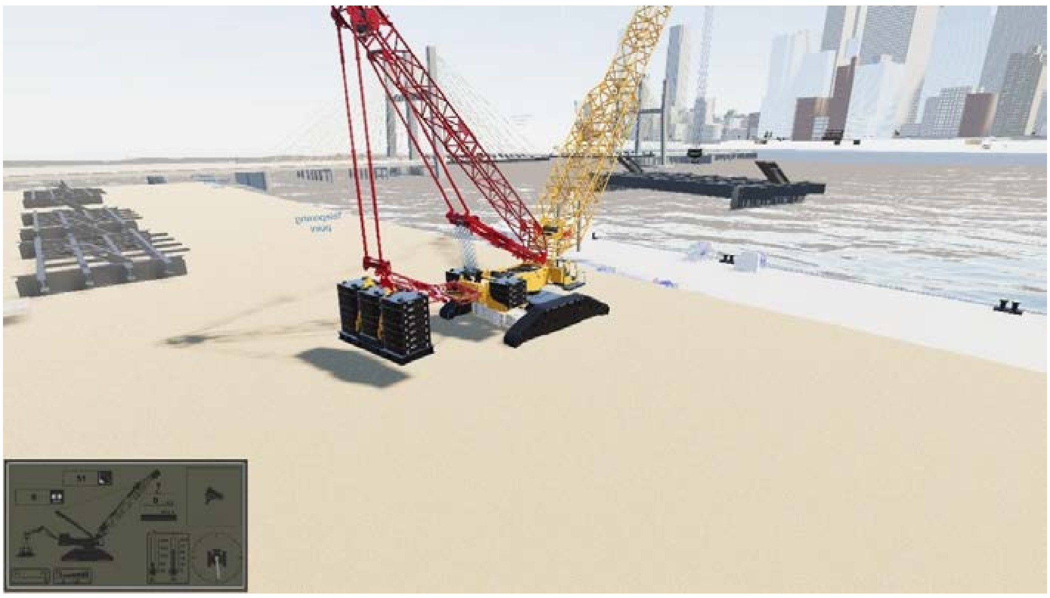

Fig. 8: Yard scene of the virtual model

4. RESULTS AND DISCUSSION

This section discusses the testing of the developed model. A group of researchers from the University of Alberta, where this study was conducted, were invited to test out the developed tool. The testing was performed in both non-immersive and fully immersive environments. In the non-immersive environment, the participant was provided with a demonstration of the keyboard buttons, as shown in Figure 9. The controlling buttons can be adjusted to fit the user preferences. All of the scenes controlling buttons are added in the instructions tab of the developed GUI. The participant should review the controlling button prior to the start of the experiment. On the other hand, in the fully immersive experience, a number of hardware pieces are used, including the VR headset and controllers. As mentioned before, the installation of the hardware is shown in Figure 2. All of the used hardware pieces were connected to the PC and added to the Unity 3D game engine. Further, in the Unity 3D platform, a few add-ons were installed to enable the VR play mode. These add-ons are the XR plugin package and the SteamVR package. The XR plugin package converts the game scene in Unity 3D from regular mode to immersive VR mode after installing the VR headset. In addition, the SteamVR package supports many functions throughout the game scenes, such as teleporting and picking/dropping functions.

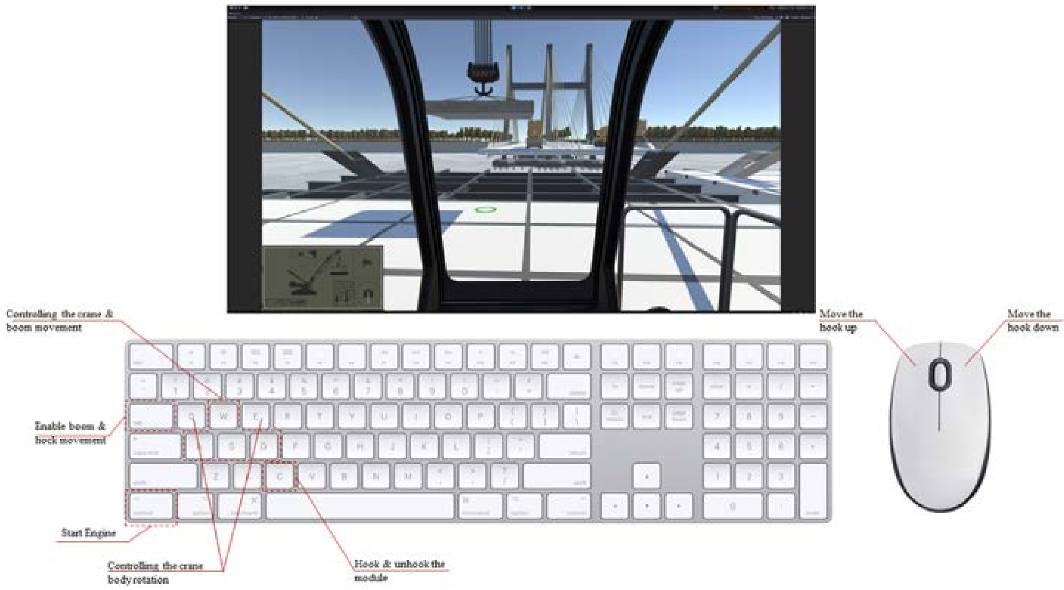

Fig. 9: Instructions of controlling buttons in the developed scenes

Participants were asked to perform tasks in the four discussed scenes. It is worth mentioning that the model was tested using a small sample of VR researchers. The next step in future research is to evaluate the model based on construction and manufacturing professionals' feedback, i.e., workers, truck operators, and crane operators. The tasks that each of the participants needed to complete can be summarized as follows: 1) in the exploring scene, the participant was asked to tour the construction site and identify several elements in the modular bridge, including steel girders, modules, precast slabs, crane locations, and stayed cables. In the immersive reality, the participant controls the movement using the VR controllers and can also teleport easily to different positions with the assistance of teleporting areas and points. When pressing on the VR controller and aiming for a teleporting point, a light is generated in the virtual environment to help the participant navigate to the selected point. This is followed by a list of questions to ensure the participant's understanding of the construction site and factory. The questions range from basic to high-level and detailed questions; 2) in the transportation scene, the participant is asked to drive the truck safely from the starting point to the pickup location. The truck path is determined by barriers and supported by signals, i.e., slow speed signs. Further, participants are also assisted by animated characters, i.e., signalers, that direct them in the right direction. In addition, the participant is also asked to park the truck next to the mobile crane in the specified location; 3) in the onsite scene, several tasks are asked to be performed by the participant. The participant is asked first to turn on the mobile crane engine, move the crane boom, and lower the hook towards the precast slab. Following that, the participant is asked to lift the slab and move to its assembly location. Finally, the participant is asked to install (drop) the slab on top of the steel module; 4) in the yard scene, the participant is asked to perform similar tasks to the previous scene. However, in this scene, the tasks are more complex because of the size of the steel module, which requires more accuracy and precision. The participants are asked for their feedback on the developed model after completing all of the mentioned tasks.

The time spent by the participants in completing the mentioned tasks was 30 minutes on average. Participants reported the high level of immersion experienced and the high level of detail in the virtual environment. It was also reported that sound effects and guidance in the virtual environment have helped participants to be more engaged in the experiment. The participants also reported that the tasks required were clear in the virtual environment and displayed GUI, i.e., clearance check, and module installation assistance facilitated safe and accurate installation. However, participants also highlighted several areas of improvement: 1) the time of the immersive VR was quite long, and participants reported a low level of focus in the last 10 minutes of the experiment (last scene); 2) some of the controlling buttons were hard to follow, especially in the crane scene where the participant needed to control the crane movement, boom rotating, hook movement, and module lifting; 3) the placement of the module was found hard by most participants as it included movement in tight spaces. The collected feedback from participants is used to improve the performance of the developed model. This is part of a continuous study that is currently conducted by the authors. It is also worth noting that the multi-user environment, which enables connections between stakeholders in the VR model, requires further testing by the participants. The cloud application of the model using WebGL and WebXR was also tested. The WebGL plugin was supported by Unity3D. The function of this tool was to build the game scenes in a format that could be deployed online. Figure 10 shows a snapshot of the cloud model. This cloud model was tested across different platforms to ensure its functionality. Furthermore, the model was also supported by the WebXR plugin. This allowed the participants to experience the developed scenes in a fully immersive manner. These tools provide accessibility to the model to multiple stakeholders. The scenes can be easily updated by the designer based on stakeholders' feedback on the cloud platform. It is also worth noting that the authors tested a few scenes of the model due to size restrictions.

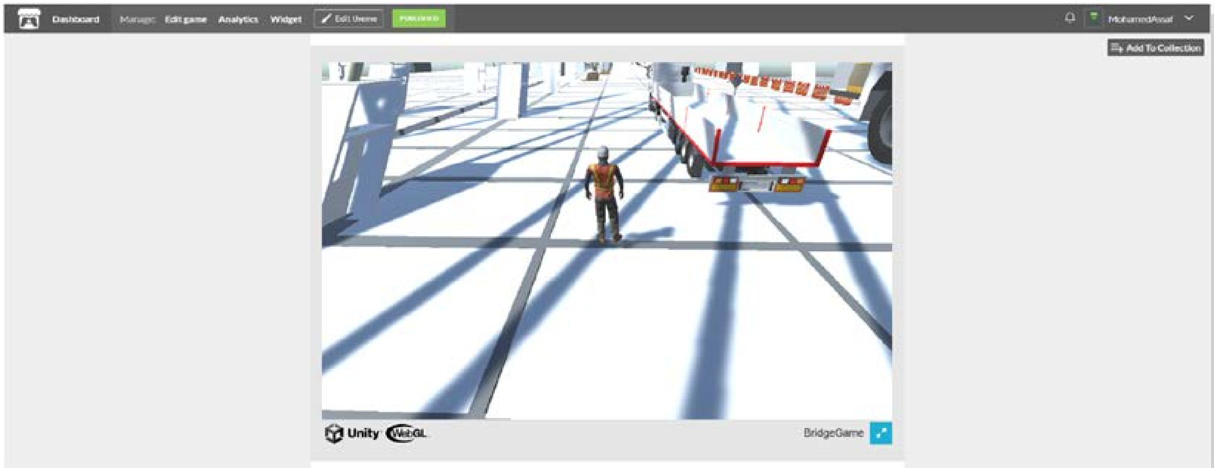

Fig. 10: Cloud platform for the developed model

5. CONCLUSION

This research was motivated by the lack of VR-OSC research when dealing with complex structures, such as modular bridges. Hence, this study contributes by developing a VR model to train participants on the processes included in the construction of modular bridges. The model is supported by a GUI that facilitates the selection of the scene of interest. This includes exploring, yard, transportation, and onsite scenes. The exploring scene allows the participant to walk around the model and explore several elements and connections. In addition, the exploring scene is supported by the steamVR feature that allows participants to navigate among different positions in the scene by pointing the VR controller in the virtual environment to the desired location. In the transportation scene, the participant can maneuver the truck according to a defined path to the pickup point following the road signals and signaler characters. This is supported by sound effects to engage the participant in the VR experience. In the onsite scene, the participant can control the mobile crane to hook the precast slab and place it on top of the steel module. This is also supported by crane and truck sound effects to engage the participant in the experiment. Furthermore, a clearance check between the hooked precast slab and surrounding objects was added to the model. The displayed clearance distance color is turned into red, and a beep sound is played when it goes below threshold to alert the participant. In the yard scene, the participant can control the crane to hook and place the module on the barge. An assistance projection area is displayed to help the participant in placing the module in the correct location on the barge.

The results show the capability of the model to immerse participants in the VR environment. Furthermore, they also showed participants' understanding of the processes through hands-on experience. However, the feedback from the participants showed a lot of areas of improvement, including the duration of the experience and the complexity of controlling the crane in the crane scenes. These areas of improvement are considered future research directions for the current study. The study provides theoretical and practical contributions. Theoretically, the study is considered a basis for a collaborative VR model that can facilitate process planning in OSC projects. Practically, the study provides an advanced VR model that can be used to connect and train OSC practitioners on various processes. Despite the contributions provided by the study, several limitations are included. The sample of participants is considered small compared to the scale of the study. However, this paper is considered a first step in continuous research that explores VR in OSC projects. Furthermore, the study theoretically explores the potential of the WebXR feature that allows easy access to the model. Future studies will be conducted to create access control for the developed model on the WebXR. In addition, the next step in this research will target the use of wearable sensors, such as eye-tracking sensors, to mitigate subjective feedback by the participants.

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PREDICTION OF COGNITIVE LOAD DURING INDUSTRY-ACADEMIA COLLABORATION VIA A WEB PLATFORM

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ABSTRACT: *Web platforms are increasingly being used to connect communities, including construction industry and academia. Design features of such platforms could impose excessive cognitive workload thereby impacting the use of the platform. This is a crucial consideration especially for new web platforms to secure users' interest in continuous usage. Understanding users' cognitive workloads while using web platforms could help make necessary modifications and adapt the features to users' preferences. Users' usage patterns can be leveraged to predict the needs of users. Hence, the pattern of cognitive demand that users experience can be used to predict the cognitive load of web platform users. This could provide insights, generate feedback, and identify areas of modification that are critical for sustaining acceptability of web platforms. Using recurrent neural network, this study adopts electroencephalogram (EEG) data as a physiological measure of brain activity to predict brain signals (cognitive load) of users while interacting with a web platform designed to connect industry and academia for future workforce development. This paper presents a Long Short-Term Memory (LSTM) based approach to develop a model for predicting users' cognitive load via EEG signals. Nineteen (19) potential end-users of the proposed web platform were recruited as participants in this study. The participants interacted with the web-platform in a real case scenario and their brain signals were captured using a five-channel EEG device. The validity of the proposed method was evaluated using root mean square error (RMSE), coefficient of determination (R^2), and comparison of the predicted and actual EEG signals and mental workload. The results revealed the reliability of the model and provided a suitable method for predicting users brain signals while using web platforms. This could be leveraged to understand users' cognitive demand which could provide insights for web platform improvements to engender users' continuous usage.*

KEYWORDS: *Cognitive load, electroencephalogram, industry-academia collaboration, long short-term memory, web platform.*

1 INTRODUCTION

To achieve a balanced blend of theory and practice, as well as adequately prepare students for a rapidly changing industry like the construction sector, collaboration between industry and academia is important. Academia differs from the industry in that the industry is known for practical application of knowledge while academia is known for teaching and research. These differences are complementary in preparing the future workforce for the workplace. Therefore, this necessitates a connection between instructors and practitioners for collaborations in future workforce development. However, there are myriads of challenges plaguing these collaborations of which a prime challenge is instructors' access to practitioners (Chandrasekaran, Littlefair, & Stojcevski, 2015). Since the outbreak of Covid-19, the internet is being increasingly used to connect individuals and communities, for example, to connect instructors to students, and buyers to sellers. The usage of the internet has been growing over the decades, with a transition from mere information sharing medium to workspaces, marketplaces, and even communities (H.-F. Lin, 2009; Schmutz, Heinz, Métrailler, & Opwis, 2009; Wellman, 2004). Dale, Basumatary, Iqbal, Khullar, and Shaikh (2022) used Facebook to connect diverse community users to archived language collections. Maher, Oropello, Roman, and Zeoli (2022) also showed how the internet was used to connect underserved communities to increase health care access and improve care outcomes. Internet-based technologies have also been leveraged to build virtual communities (H.-F. Lin, 2009). Therefore, a web-based platform could be used to connect instructors to different practitioners who are willing and able to provide complementary input in course offerings. Hence, a web-based platform was designed to give instructors improved access to practitioners who could provide complementary inputs in instructors' pedagogical effort and support the preparation of students for the industry. However, during interaction with web-based platforms, there is a risk of cognitive overload. Cognitive overload is an indicator of non-intuitive interface, poor presentation of information which requires more efforts to interact with thereby exhausting cognitive resources. Therefore, to ensure that the web platform for connecting instructors with practitioners has little or minimal downsides, it is important to ensure it has minimal cognitive demand on users.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Anthony Yusuf, Abiola Akanmu, Adedeji Afolabi, Homero Murzi, *Prediction of Cognitive Load during Industry-Academia Collaboration via a Web Platform*, pp. 57-68, DOI 10.36253/979-12-215-0289-3.06

High cognitive load has been identified as an indication of web usability problem (Albers, 2011) but this is not always the case. Users' performance and success in the use of web-based platforms depends not only on the web platform but also on users. This is because human cognitive resources at a point in time are limited, unstable, and vary from person to person. Also, the perceived cognitive demand for the same activities varies among people (Das, Chatterjee, & Sinha, 2013), for example due to differences in prior knowledge (Seufert, Jänen, & Brünken, 2007), users skill level (Kumar & Kumar, 2016), and amount of cognitive resources available (Tracy & Albers, 2006). In addition, regardless of intrinsic features of a web-based platform that could impact users' cognitive load, other extrinsic factors such as lack of adequate sleep, temporal demand, and stress (Tracy & Albers, 2006) could reduce the amount of cognitive resources available to users at a point in time. Therefore, due to these varying and fluctuating extrinsic factors, a user can experience different levels of cognitive demand on the same web-based platform at different times even when the platform is not changing. Majority of prior studies (Hewitt & He, 2022; F.-R. Lin & Kao, 2018; Mills et al., 2017; Schmutz et al., 2009) focused on detection of cognitive load and the impact of web-platforms' intrinsic characteristics on users' cognitive load with little or no attention on extrinsic factors that are user-dependent which also impact cognitive demand. This represents a major limitation to the generalizability of user experience on the same web platform due to the fluctuation and differences in human cognitive resources. This also accounts for disparities between usability evaluations and real-world scenarios which usually skewed the results of several user testing research. Hence, one-size-fits all approaches cannot meet users' unique and differing needs.

Therefore, to address the dynamism in web-platform usage because of the varying and unstable nature of cognitive resources, adaptive and personalized website design would be beneficial (Desai, 2021). To achieve this, (Adomavicius & Tuzhilin, 2005) recommended leveraging usage patterns to predict the needs of users. A reliable prediction of cognitive load is a fundamental step toward adaptive design (Appel et al., 2019). Hence, the pattern of cognitive demand that users experience can be used to predict the cognitive load of users. This could also help to generate feedback and identify areas of modification that are critical for sustaining acceptability of web platforms. In addition to subjective measures (e.g., NASA TLX), electroencephalogram (EEG) is a growing objective measure of cognitive load in human computer interaction. This has been used by previous studies (Caldiroli et al., 2023; Kumar & Kumar, 2016) to assess cognitive load in web-platform usage. Previous studies (Appel et al., 2019; Herbig et al., 2020) have focused on predicting cognitive load with other physiological measures (such as eye tracking metrics, heart rates, and galvanic skin response) using machine learning. Most previous studies (Caldiroli et al., 2023; F.-R. Lin & Kao, 2018; Mills et al., 2017) focused on using EEG to detect cognitive load in web platform usage. Only a few studies such as (Friedman, Fekete, Gal, & Shriki, 2019; Mills et al., 2017; Yoo, Kim, & Hong, 2023) used EEG for prediction of cognitive load in web platform usage. Mills et al. (2017) leveraged EEG spectral features using partial least squares regression to develop a model to predict cognitive load during interactions with an intelligent tutoring system. Yoo et al. (2023) developed a long short-term memory (LSTM)-based machine learning model to predict the degree of cognitive load using EEG data. The study showed that LSTM had the highest accuracy of 87.1% compared to random forest (64%), AdaBoost (64.31%), support vector machine (60.9%), XGBoost (67.3%), and artificial neural network models (71.4%). Using EEG data for prediction of cognitive load, Friedman et al. (2019) assessed different machine learning predictive models and reported that XGBoost has the highest predictive power compared to random forest, artificial neural network, and simple linear regression models. Therefore, if a web platform is held constant over time, users' cognitive demand can be predicted with EEG signals as they interact with the platform. Hence, this study leverages EEG signals to develop a model for predicting the cognitive demand of a web platform designed for industry-academia collaborations. The results of predicting users' cognitive load could help identify patterns in the usage of the platform which could inform necessary modifications to ensure optimum usability that could influence users' acceptance and intention to use the proposed web-based platform

2 BACKGROUND

The success of new information systems hinged on users' acceptance (Davis, 1985). However, high cognitive load could affect user's satisfaction as well as acceptance of a new web-platform. For example, high cognitive load is an indication of web usability problems (Albers, 2011). Hu, Hu, and Fang (2017) demonstrated that cognitive load can affect user satisfaction with a website. This could affect users' revisit, trust, and loyalty (Desai, 2021). Hewitt and He (2022) showed that difficulty of task to be performed and web page contrast could impact users' cognitive demand and perceived usability. Schmutz, Roth, Seckler, and Opwis (2010) revealed that mode of presentation of information on web platforms impacts users' perceived cognitive load. Examples of other problems associated with web-based platforms which could affect the cognitive load of users include confusing link name or description, horizontal scrolling, and atypical interface design which negate users' mental model (Albers, 2011). The cognitive demand of web-based platforms is crucial because human cognitive resources are limited. Hence, there is a risk of web-platforms requiring more cognitive resources than what users possess, which results in cognitive overload (Albers, 2011). Despite design principles, users of web platforms could be overwhelmed or confused because of information overload and/or excessive obstacles to overcome before locating the right information. Cognitive overload could interfere with mental processing of information which could cause users to exit a web page or even fail to locate appropriate content (Albers, 2011). Other manifestations/impact of cognitive overload on web users include task shedding, increase in frustration, multiple mistakes, lack of attention to detail and disregard of content (Albers, 2011; Kumar & Kumar, 2016). As cognitive demand increases, users' performance plummets (Tracy & Albers, 2006). Hence, the need to assess cognitive load of users as they interact with web-based platforms.

Though originated from psychology, assessment of cognitive load has translated into physiological sensing where objective measures such as EEG are increasingly being used to complement subjective measures (Kumar & Kumar, 2016). The limitations of subjective measures (such as bias and inability to currently recall actual experience or perception) make objective measures (e.g., EEG) growing methods for assessing cognitive load. Through electrodes on the scalp, EEG collects brain signals resulting from cognitive processes taking place in the brain (Kumar & Kumar, 2016). These signals vary depending on the type of activities in the brain and correspond to cognitive load (Mills et al., 2017). By leveraging deep learning techniques, EEG signals can be used to predict cognitive load via real time data from brain signals. Prior studies have demonstrated the efficacy of EEG to predict the cognitive load in different contexts (Moghar & Hamiche, 2020; Salman, Heryadi, Abdurahman, & Suparta, 2018; Yoo et al., 2023) using Recurrent Neural Networks (RNN). RNN are deep learning techniques commonly used for time series forecasting of sequential data (Qin & Bulbul, 2023). However, major downsides of RNN include the time intensive nature of traditional RNN and difficulty in training the models because they are prone to vanishing and exploding gradient problems (Van Houdt, Mosquera, & Nápoles, 2020). To circumvent this challenge, advanced architectures like LSTM are being used in diverse contexts to develop prediction models for time series. For example, in prediction of mental workload during construction task using augmented reality head mounted display (Qin & Bulbul, 2023), stock market prediction (Moghar & Hamiche, 2020), and weather forecasting (Salman et al., 2018). LSTM consists of input layer, output layer and an intermediary LSTM layer (or hidden layer) (Moghar & Hamiche, 2020). The input layer receives data as input, while the output layer determines data that will be output. The hidden layer is made up of memory cells and three gates that are in charge of updating the cell state. LSTM is a gradient-based method used for capturing long-term dependencies in sequential data (Hua et al., 2019). The primary component of LSTM that enabled this capability of LSTM is the memory block (Van Houdt et al., 2020). Memory block (or LSTM cell) is a subnetwork comprising a memory cell (also known as cell state) and three gates (namely, input gate, output gate and forget gate) (Staudemeyer & Morris, 2019). The memory cell retains the temporal state of the neural network while the gates control the flow of information. The input gate manages the inflow of new information into the memory cell using Equation 2 and 3 and updates the memory cell by Equation 4. The amount of existing information which remains in the current memory cell is controlled by the forget gate as illustrated in Equation 1. The output gate regulates the amount of information for computing the output activation of the memory block and how it propagates to the rest of the neural network (Hua et al., 2019) using equations 5 and 6. The structure of the LSTM cell is shown in Figure 1.

$f_t = \sigma(W_f [h_{t-1}, x_t] + b_f)$ ...Eqn. 1
$i_t = \sigma(W_i[h_{t-1}, x_t] + b_i)$ ...Eqn. 2
$\tilde{c}_t = \tanh(W_c[h_{t-1}, x_t] + b_c)$ ...Eqn. 3
$c_t = ft \odot c_{t-1} + it \odot \tilde{c}_t$ ...Eqn. 4
$o_t = \sigma(W_o[h_{t-1}, x_t] + b_o)$ ...Eqn. 5
$h_t = ot \odot \tanh(c_t)$ ...Eqn. 6

Weight matrices for the forget gate, input gate, cell state and output gate are denoted by W_f, W_i, W_c, W_o. In the same order, b_f, b_i, b_c, b_o represent the bias vectors. Elementwise (Hadamard) multiplication is denoted by $\odot$, logistic sigmoid function by σ, and the hyperbolic tangent function by tanh. h_t and c_t represent the hidden state and cell state at time t respectively.

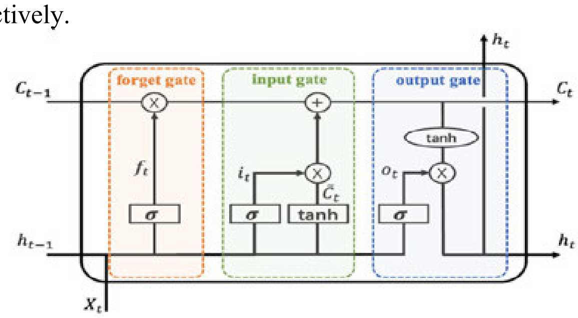

Fig. 1: Architecture of LSTM network.

Mental workload can be estimated from spectral power which represents the brain rhythm's energy (Qin & Bulbul, 2023). A positive relationship existed between cognitive load and theta rhythm power, whereas a negative relationship exist between cognitive load and alpha rhythm power (Gevins, Smith, McEvoy, & Yu, 1997). Hence mental workload can be calculated using equation 7 similar to Qin and Bulbul (2023).

$$\mathrm{MW(t)} = \frac{\theta f\,(\mathrm{t})}{\alpha\, p(\mathrm{t})} \quad \text{......Eqn. 7}$$

MW(t) represents the mental workload at time t; θf(t) and αp(t) are the mean spectral power of theta and alpha rhythm at time t respectively.

3 METHODOLOGY

3.1 Overview of the Web Platform

The web platform in this study is designed to be a collaborative network of instructors and practitioners for future workforce development. The aim of the platform is to improve instructors' access to practitioners who could provide practical supplementary inputs in construction engineering education to aid students' preparedness for the industry. The potential users of the platform are instructors in construction-related programs (such as Building Construction, Architecture, Civil and Environmental Engineering as well as Construction Engineering and Management) and construction industry professionals. The platform was designed by leveraging participatory design, interaction design and user-centered-design principles (Freire, Arezes, & Campos, 2012). Users' input and participation in the design process were ensured through usage research. Usage research was used to elicit pertinent information from end users. The information elicited served as inputs for the design of optimal graphic user interface of the platform. By leveraging heuristics design principles for user interface design (Nielsen, 1994), the platform was designed to be typical to other platforms that potential users are familiar with. This is to ensure that the platform operational procedure is similar to users' mental mode which could enhance ease of use of the platform as well as users' acceptance. To use the platform, an instructor is required to sign up, verify email address, complete profile, submit request for course-support, view recommended practitioners from the platform and select preferred practitioner to meet the course-support request. The course-support requests include site visits, guest lectures, seminars, workshops, and other activities that allow students to interact with practitioners under the guidance of an instructor. The platform was designed using JavaScript programming language. A relational database management system (MariaDB) was adopted with Node.js as server.

3.2 Experimental Design

After a brief introduction of the platform to participants. The procedure of the experiment was explained. All participants provided their informed consent by signing the consent form. The participants interacted with the web-based platform. Each participant was required to sign up on the platform. Thereafter, participants verified their email address before first login. Upon login, the participants were required to complete their profile after which they requested a course-support from practitioners. After a request for course-support, participants viewed recommended practitioners to meet their course support request. Out of these recommendations, instructors made a selection. Every session of the experiment was conducted under similar conditions.

3.3 Participant and Study Approval

Nineteen (19) participants were recruited after the research protocol was approved by the Virginia Tech Institutional Review Board. The participants include both male and female professors (the proposed end-user of the web-based platform) with varying degrees of experience, different job titles and from diverse construction-related academic programs such as civil and environmental engineering, building construction, architecture, and construction engineering and management.

3.4 Data Collection

As participants use the web-based platform, their cognitive load was objectively measured via braai signals using an electroencephalogram (EEG) device called EMOTIV Insight. EMOTIV Insight has five channels, namely AF3, AF4, T7, T8, Pz with semi-dry polymer sensors and two reference sensors (CMS and DRL). The channels are arranged according to the 10/20 international EEG system. EMOTIV Insight has a sampling rate of 128 samples per second per channel for EEG signal with frequency response of 0.5-43Hz, digital notch filters at 50Hz and 60Hz. The device has Bluetooth connectivity which can be connected to a computer or mobile device with Bluetooth V5.0. EMOTIV Insight provides coverage of the frontal, temporal and parietal lobes which are associated with cognitive effort (Kumar & Kumar, 2016). The EEG recording was about ten (10) minutes on average per participant. An overview of the methodology is shown in Figure 2.

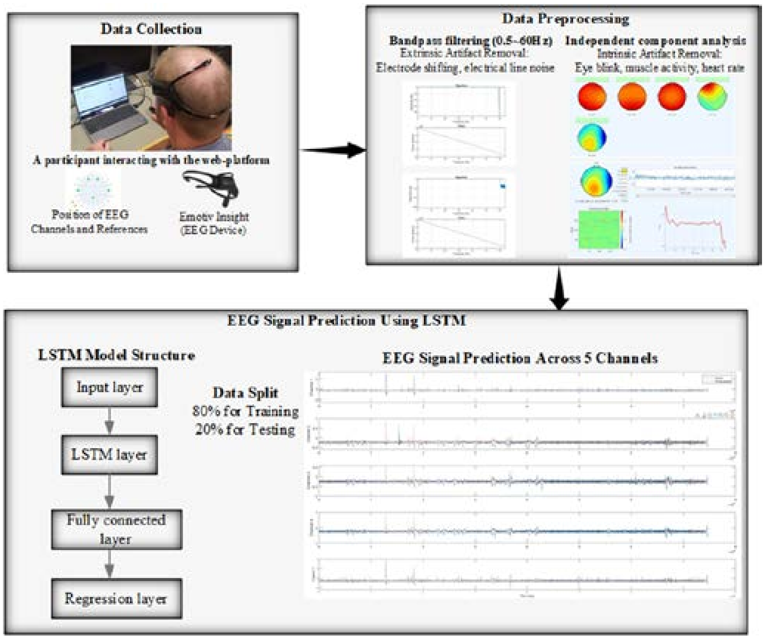

Fig. 2: Overview of methodology.

3.5 Data Preprocessing and Analysis

The raw EEG data collected with the EmotivPRO app was cleaned. Thereafter, the processes highlighted below were carried out.

3.5.1 Artifacts removal

EEG signals are susceptible to diverse categories of artifacts which represent noise/interferences to signals of interest. These artifacts are either intrinsic or extrinsic. Intrinsic artifacts are generated by EEG user's body movement such as blinking and muscle activity. Extrinsic artifacts originate from external factors such as shifting of electrode, noise from electrode wiring and surroundings noise (Jebelli, Hwang, & Lee, 2018). According to Urigüen and Garcia-Zapirain (2015), these artifacts are usually small when the EEG device is used in a somewhat stationary position as it was in this study. Both intrinsic and extrinsic artifact removals were done using EEGLAB. The cleaned EEG data in CSV format were converted to MATLAB file and imported into EEGLAB. The data was mapped and structured using 5-channel location. The extrinsic artifacts were removed using basic band pass filter range of 0.5Hz to 60Hz. As recommended by Delorme and Makeig (2004), Extended Infomax method was used to decompose the EEG data through independent component analysis (ICA). The data was decomposed into 5 components, displayed with scalp heat maps and intrinsic artifacts were rejected.

3.5.2 Data Processing

Five (5) brain wave frequency bands were captured by each of the five (5) electrodes of the EEG device (EMOTIV Insight) used in this study. These frequency bands include Theta (4-8Hz), Alpha (8-12Hz), Low Beta (12-16Hz), High Beta (16-25Hz), Gamma (25-45Hz). The cleaned data for all the nineteen participants from the five (5) channels of the EEG device were used for the analysis. There were 79936 data points on average for each participant for an average recording time of 10 minutes. The data points were split into 80% and 20% for training and testing respectively.

3.5.3 Prediction framework

The preprocessed EEG data was used to train the LSTM network for prediction of EEG signals. Open loop forecasting was adopted because true values of brain signals (representing cognitive load) from EEG were used to train the LSTM network for prediction. Similar to Kingma & Ba (2014), Adaptive Moment Estimation which is an extension of the stochastic gradient descent algorithm was used for optimization with a learning rate of 0.001.

To ensure that the loss is as small as possible an epoch of 250 was adopted for training the model. Root Mean Square Error (RMSE) was used to calculate the loss function to determine the performance of the model. The LSTM layer has 128 hidden units or memory cells to capture and store information over time, which enables the LSTM network to process sequential data effectively. The hidden units determine the amount of information learned by the layer. Both the sequence input layer and the fully connected layer of the LSTM regression neural network have sizes that match the number of channels of the input data.

3.5.4 Mental workload

Because it is not possible to directly measure mental workload from EEG signals, the signals were converted into frequency domain. This conversion enabled the calculation of the average spectral power of particular brain rhythms, hence, the Power Spectral Density (PSD) of the signal was calculated. PSD is a measure of the mean power distribution of a signal over a specific timeframe with the unit showing energy per frequency (Qin & Bulbul, 2023). The mental workload was estimated using equation 7 for both the actual and predicted EEG signals.

4 RESULTS AND DISCUSSION

4.1 Performance Evaluation

The performance of the predictive model was evaluated using RMSE. The RMSE shows the difference between the predicted and actual values of the EEG signals. Table 1 shows the RMSE for all the test participants. The average of the RMSE was 0.0674. The RMSE of the test participants' datasets were very low (<0.037) except for the third participants whose RMSE was 0.1607 which skewed the average of the RMSE to 0.0674. However, the low RMSE of the other test participants' datasets reveal the high predictive power of the LSTM model by indicating marginal difference between the actual and predicted EEG signals. This agrees with Miyamoto, Tanaka, and Nakamura (2022) who posited that the closer RMSE is to zero the better. The high RMSE of the third participant in the test dataset could be attributed to insufficient data points. All other participants had more than 74,000 data points while the third participant had about 58,500 data points amounting to a difference of 16,000 data points. Also, the EEG recording time of the participant was very short and fell below the average duration. This agrees with Pyo et al. (2018) who opined that low RMSE might be because of insufficient data points. In addition, although 58,500 data points seem considerably high, this result reveals that prediction models require large amounts of data for accurate forecasting. This position is also supported by Ettinger et al. (2021), even though there are no fixed number of data points required for predictive models. However, considering other factors such as complexity of problem, desired performance and complexity of model, this result could provide a guide for future research.

Table 1: RMSE for test participants.

Test Participants	1	2	3	4
RMSE	0.0356	0.0367	0.1607	0.0367

The performance of the LSTM prediction model was further assessed as shown in Figure 3 by comparing the predicted and actual EEG signals of the test dataset for the five (5) EEG channels. The comparison reveals that the predicted EEG signals follow a very similar pattern as the actual EEG signals. Although there were minor deviations where the path of the predicted signals did not align with the actual EEG signals, to a large extent, the model was able to accurately predict sudden and subtle fluctuations. However, it appears that the model was able to predict subtle fluctuations better than sudden drastic changes in the EEG signals. Overall, the predictive model can be adjudged reliable especially in predicting subtle fluctuations in the EEG signal. To further show the performance (validity) of the predictive model, scatter plot was used to plot the predicted values and the actual values of the test data set for each EEG channel (see Figure 4).

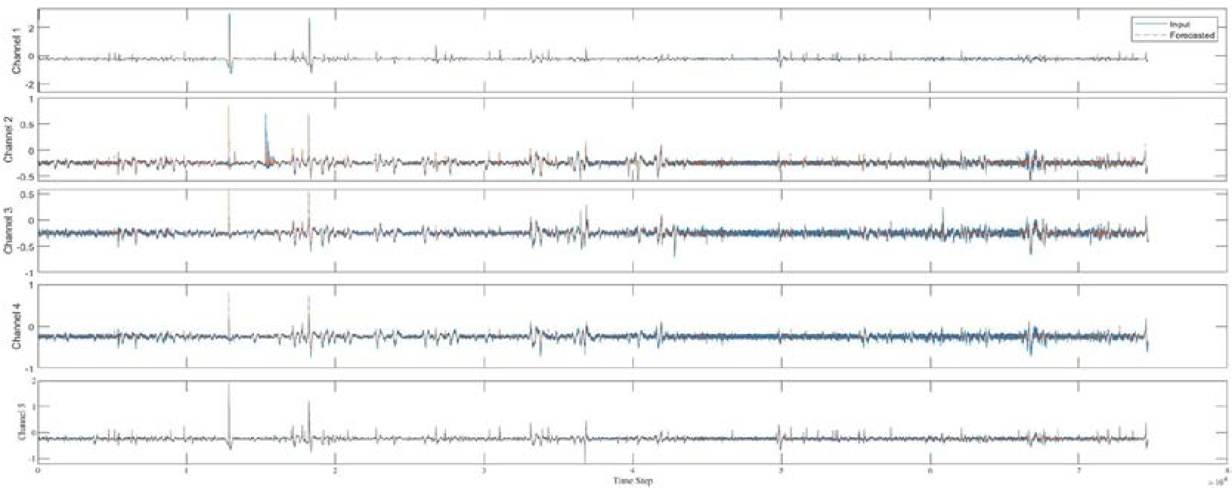

Fig. 3: Comparison of predicted and actual EEG signals for the test dataset across the five EEG channels.

The scatter plots in Figure 4 and the R^2 in Table 2 show that the model was able to explain a significant proportion of the variability in the actual EEG values. R^2 is the coefficient of determination which indicates the goodness-of-fit of the regression model. Given the low RMSE for the test participants and the high R^2 for the channels, it is evident that the model captured the underlying pattern in the data effectively, and the predicted values are very close to the actual values. The model could therefore be considered accurate because as Alexander, Tropsha, and Winkler (2015) explained, RMSE is a useful indicator of a model's practical value. The high R^2 values show that a significant portion of the underlying patterns and relationships in the actual data is accounted for by the predictions made by the LSTM model. This is because according to Chicco, Warrens, and Jurman (2021), RMSE is a measure of the average errors between predicted values and actual values while R^2 explains the amount of variance in the data that the model could explain. Hence, the overall value of a model has been defined by its accuracy and precision and as well as by its effectiveness in elucidating the variability in datasets (Coulibaly & Baldwin, 2005; Qin & Bulbul, 2023). Also, given that the low RMSE values were for the test participants while the high R^2 values were for the EEG channels, it is shown that on the overall for a participant, the model was able to achieve little error between the actual EEG signals and the predicted EEG signals, and for each EEG channel, the model was able to explain a significant portion of the variability in the data for prediction. Hence, the model is able to give reliable prediction of participants' EEG signals.

Table 2: R^2 for each channel.

Channel	AF3	T7	PZ	T8	AF4
R^2	0.9336	0.7683	0.8022	0.7541	0.8854

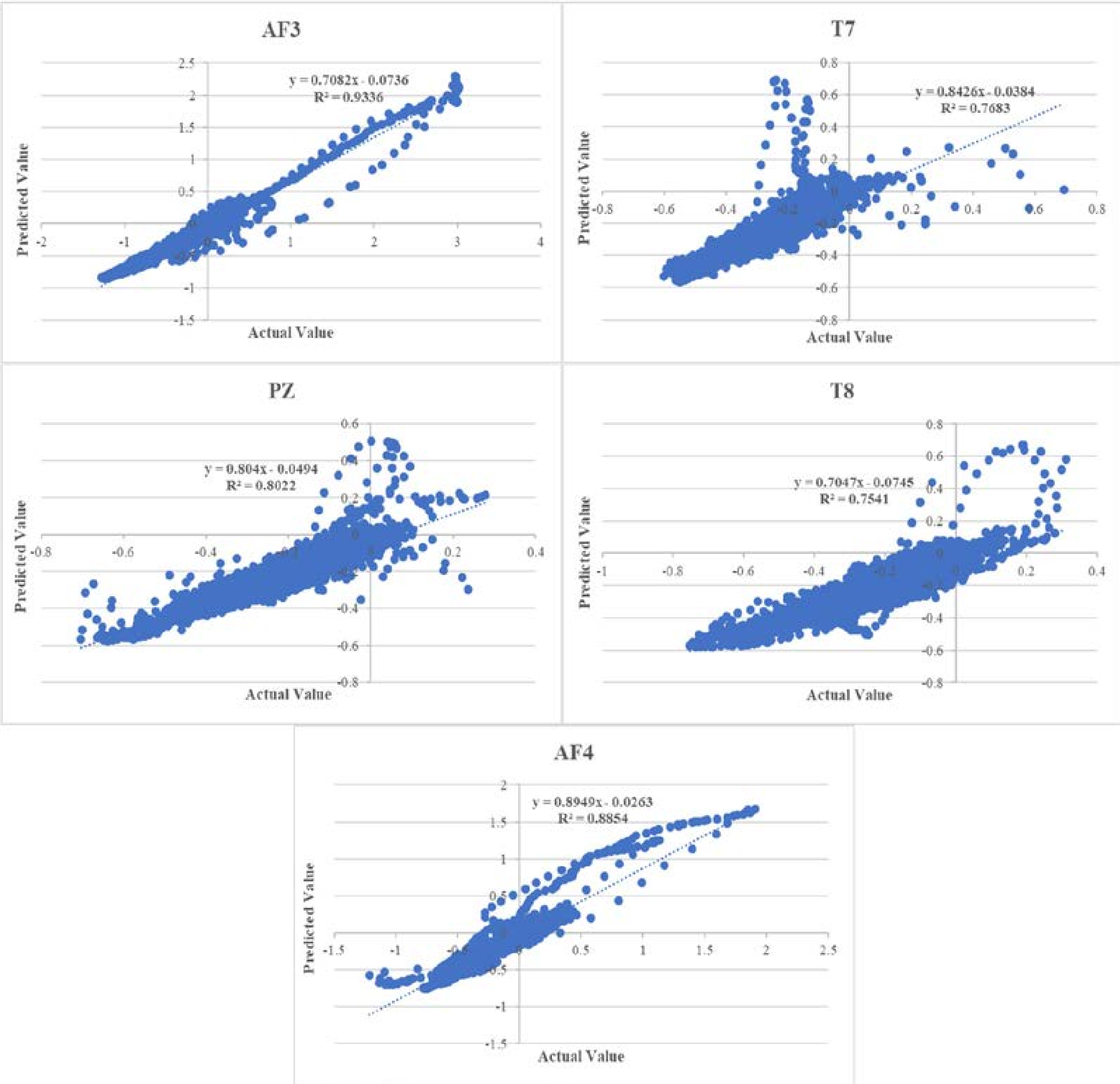

Fig. 4: Scatter plots showing the predicted and actual values for the 5 EEG channels.

As shown in Table 2, the R^2 values are ≥ 0.7541. Channel AF3 has the highest R^2 value, this is followed by channel AF4, PZ, T7 and T8 respectively. The scatter plots show the linear relationship between the predicted and actual EEG signals. Although as shown in Figure 4, there are few data points that deviated from the linear relationship in each EEG channel, a great proportion of both the predicted and actual EEG values fit into the linear relationship. For example, the lowest R^2 value is 0.7541 shows that about 75.41% of variance in the actual EEG signals is accounted for by the predicted signals. According to Coulibaly and Baldwin (2005), R^2 values in the range of 0.8 - 0.9 are considered acceptable and those > 0.90 are considered very satisfactory. Only three EEG channels (AF4, PZ and AF4) fall within this range. However, as revealed by Alexander et al. (2015), RMSE is a more informative indicator of a model's usefulness compared to R^2. This is because, the value of a model should be based on its accuracy and precision and not on its explanatory power of variability in a particular data set (Alexander et al., 2015). Chicco et al. (2021) also noted that R^2 value can be quite low even when dealing with a fully linear model, and the opposite is also true. Therefore, overall, the results show that brain activity of users using a web-based platform can be reliably predicted with EEG signals.

4.2 Mental Workload

Figure 5 shows the scatter plot of the predicted mental workload plotted against the actual mental workload. According to Coulibaly and Baldwin (2005), the R^2 value (> 0.90) was very satisfactory. This shows that the predicted mental workload matches the actual mental workload which further reinforces the efficacy of the LSTM model to learn and predict the cognitive load of users during industry industry-academia collaboration via a web platform. The results reveal that 92.50% of the variance in the actual mental workload can be explained by the predicted mental workload. This provides a reliable prediction of mental workload of users in industry-academia collaboration via a web platform. This potential of LSTM model to predicted cognitive load has been corroborated by earlier studies such as Salman et al. (2018) and Qin and Bulbul (2023).

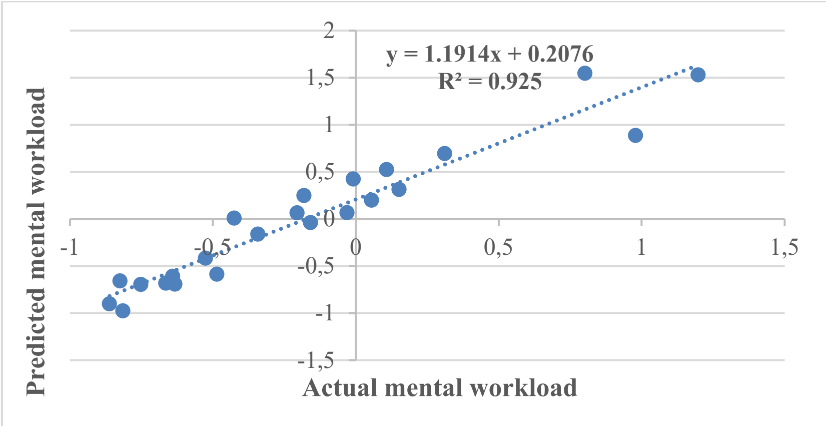

Fig. 5: Relationship between actual and predicted mental workload.

5 CONCLUSION, LIMITATIONS AND FUTURE WORK

Cognitive load is a major consideration in the design and usage of user interfaces because it could influence users' attitude towards the web platform as well as continual usage. Through web platforms, the internet is being leveraged to connect instructors in construction-related programs with construction industry practitioners who could support their pedagogical efforts in preparing students for the workplace. Using LSTM, this study assessed the effectiveness of EEG-based prediction of brain signals (representing cognitive load) as instructors interact with the web platform designed to connect them with practitioners. The results demonstrated the accuracy and reliability of the LSTM model to predict EEG signals as users interact with the web platform. The model was able to predict subtle fluctuations better than sudden drastic changes in the EEG signals. The results showed low RMSE and high R^2 values which indicate that the model's predictions are close to the actual values, and it is explaining much of the variability in the data. The efficacy of the model to predict EEG signals could be leveraged to understand users' pattern of cognitive demand in human-computer interaction. This pattern of users' cognitive demand could provide a better understanding of the cognitive resources expended by users as they interact with the web platform. This is critical because users' cognitive resources and cognitive demand varies due to both intrinsic and extrinsic factors hence a one-time detection of cognitive load might not provide adequate insights. The prediction of EEG signals could be used to understand users' usage patterns and necessary modifications required to enhance interface functionality, navigation, content integration as well as user experience. This is crucial for new web platforms which users are unfamiliar with and which could operate differently from their mental model. Also, the process of users' acclimatization with the platform as well as the impact of learning curve in using the web platform could be better understood through the prediction model. The study has some limitations which should be acknowledged. Although the sample size is adjudged adequate, using a higher sample size could yield better results. Also, LSTM was used in this study, future work could focus on using different network models for comparison of accuracy and reliability. Future work could likewise explore achieving lower RMSE and higher R^2.

ACKNOWLEDGMENT

This research is based on work supported by the National Science Foundation (NSF) via Grant No. 2201641. Any opinions, findings, and conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of NSF.

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TRANSITIONING FROM 2D TO VR IN DESIGN REVIEW – RESISTANCE TO ENGAGEMENT

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ABSTRACT: *Although immersive virtual reality (VR) has been shown to facilitate collaborative understanding of a design, many users remain resistant to its use. Moreover, there is currently a lack of real-world studies investigating why certain users (e.g., architects) are resistant to use VR during design reviews. The aim of this study is to understand the resistance that influence client representatives' and architects' interaction with a VR-system that supports both fully- and non-immersive experiences of the virtual environment. Data were gathered from three VR-workshops, which were part of 3 design review sessions of a new elementary school. Additional data were gathered from four semi-structured interviews with both the architects and client representatives participating in all workshop sessions, the interior architect involved in the project as well as an additional six semi-structured interviews. These additional six interviews involved exterior architects from different firms, who had previously used VR for both informative and design review purposes. The findings suggest that client representatives and the architects had initially been resistant to use VR during the design reviews, but their attitudes changed progressively during the three workshops, in particular that of the architects. The findings also indicate that interactive features in VR (e.g., object manipulation, multi-user) help end users negotiate design requests more efficiently and make informed decision-making. This paper highlights how immersive VR could improve the design review process.*

KEYWORDS: *Virtual Reality, HMD VR, design process, design review, spatial understanding, end-users.*

1. INTRODUCTION AND RELATED WORK

Fully immersive Virtual Reality (VR) has emerged as a potential alternative to traditional information and visualization media (e.g., 2D drawings, 3D models) where users are surrounded by a virtual environment of the building design. This experience of users "stepping into the design" is referred to as an immersive experience (Castronovo et al., 2013; Johansson, 2016). When fully immersed, users can experience the design from a user-centric viewpoint, i.e., an ego-centric frame of reference (Paes et al., 2023), which provides clearer visual cues (e.g., size, shape, location) (Hermund et al., 2017). Enhanced visual cues not only help users better perceive volumetric qualities of the building design than when 2D drawings and 3D models are used (Chowdhury & Schnabel, 2020), but also help users gain a more representative understanding of the final building design (Nikolić & Whyte, 2021). It is important to note here that 3D models viewed on a traditional screen are considered non-immersive VR (Castronovo et al., 2013), e.g., when 3D models are displayed on a computer monitor, projector screen or a multitouch table (Dorta et al., 2016), the users are not immersed even though they do view a virtual environment. In contrast, immersive VR-systems provide either a semi-immersive experience (i.e., experiencing the virtual environment through stereoscopic displays) or a fully-immersive experience (i.e., with head mount display (HMD) and motion-tracking). Studies have also explored how hybrid design environments, (i.e., combining traditional design techniques such as sketching by hand with immersive ones like VR), influence users' understanding of the design. For instance, Okeil (2010) showed how design team members, interacting with available 3D computerized sketching feature combined with a visual understanding enabled by a semi-immersive CAVE system, were able to efficiently explore and iterate on different design ideas. More specifically, by viewing the design that had been drawn in the non-immersive environment, design team members could immediately see the outcome of their design decisions in the semi-immersive environment, resulting in a more rapid cycle of testing and validating of different designs.

In the context of users' interacting with different VR-systems, interactive features in fully-immersive VR such as object manipulation (Wolfartsberger, 2019), multi-user (Truong et al., 2021) and multi-scale (Sateei et al., 2022) have shown to facilitate a mutual understanding of the design between end-users and design team members. For example, the ability to combine multi-user and object manipulation to use task-based scenarios during design review has shown to accelerate decision-making when resolving design issues. Specifically, by enabling furnishment and collaborative review of the virtual environment in real-time, end-users can better understand which layouts support building occupants' work tasks whilst also reducing the overall lead-time of the design process (Roupé et al., 2020). Accordingly, task-based scenarios in VR shift design review from interpreting the design to understanding building occupants' daily work tasks (Nikolić & Whyte, 2021). This understanding of

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)

building occupants' daily work tasks is then more likely to result in collaborative practices such as Co-design where the end-users become part of the design team (Caixeta et al., 2019; Roupé et al., 2020).

However, although several studies have shown the benefits of using VR in the design process, few have explored end-users' and design team members' engagement in using VR for design review purposes (Maftei et al., 2018). For example, questions remain as to how a collaborative understanding for the design may be facilitated with VR when VR as an information and visualization medium, whether semi- or fully-immersive, is primarily used as a presentation tool by architects (Achten, 2021; Scheer, 2014). One explanation might be the lack of knowledge on how to use VR in workflows where 2D drawings and 3D models are used (Zaker & Coloma, 2018). Another explanation highlighted by the literature is that due to the lack of real-case studies, stakeholders such as architects are resistant to using VR due to not knowing when in the building process to use it. Specifically, there is an initial resistance to using VR in a project setting, and its value in understanding end-users' design preference is often realized too late in the project when time constraints arise (Belek Fialho Teixeira et al., 2021). Therefore, the focus of this study is twofold: 1) to understand client representatives' and architects' resistance to engage with VR-systems with support for both fully- and non-immersive experiences of the building design and 2) how architects and client representatives collaborate to resolve design issues when VR is used in a design review context.

1.1 Clients' and architects' use of VR for design review

Studies have explored the advantages of using VR in the context of design review and from a client perspective. One example is that end-users such as client representatives seem to become less reliant on the design team for their interpretation of the design (Kim et al., 2016), which could help reduce decision-making time during design review (Liu et al., 2020). Another example is a study by Liu et al. (2020) where they found that semi-immersive VR did not only help those who have difficulties interpretating 2D drawings but also helped project members who had not yet seen the design to better understand it. Similarly, in an experimental study, Umair et al. (2022) observed that participants' task completion time was shorter in fully immersive VR compared to 2D drawings when identifying design issues. Studies have also investigated challenges to wider adoption of VR. Examples of these challenges are clients' lack of knowledge of how VR-based practices should be adopted (Zaker & Coloma, 2018) and the lack of real-life case studies that explore how decision-making that is typically done in later phases of the building process, could be made already in earlier design phases (e.g., concept design phase) (Nikolić & Whyte, 2021).

From an architect perspective, VR is seen as one of many available information and visualization mediums (Kim et al., 2016). Whilst drawing has been the traditional communication tool of architects (Scheer, 2014), recent years have seen a continuous increase in use of a 3D model-based approach when building information modelling (BIM) is used in project, whether it is throughout the entire construction process (Disney et al., 2022) or only limited to the design process (Smith, 2016). In this context of using 3D models in the design process, VR models have been used when extracting them from the BIM model (Johansson, 2016), resulting in architects able to showcase the building design in VR. Still, the literature shows that architects maintain control over decision-making in the design process when using VR as they have when 2D drawings are used (Scheer, 2014). An example is the use of pre-defined viewpoints in the VR model during architectural walkthroughs of the building design. The argument for using pre-defined viewpoints is that it prevents end-users from being overwhelmed with too much detail in the virtual environment, which ensures that end-users maintain focus on resolving intended issues during design review (Castronovo et al., 2013). Additionally, previous work highlights how VR challenges the hierarchical position of architects, who are used to predictable and controlled working methods, such as when 2D drawings are used (Cruickshank et al., 2013; Scheer, 2014).

Beyond these challenges relating to both client and architects, there is a lack of studies on how use of VR can affect stakeholders' acceptance of VR over time and how the interactions between architects and clients may be affected. While many research efforts have explored the use of VR-based design review in real-life cases, most of these have primarily concentrated on using VR in one-time sessions or semi-immersive use (e.g., power wall) rather than fully-immersive (e.g., HMD) VR-systems (Liu et al., 2020). Few have explored how the use of VR over several design review sessions, with the same stakeholders, influences their receptiveness or reluctance to use the VR-system. However, these studies do not delve into the impact of the shifting conventional roles between architects as "experts" and clients as "non-experts" on the design when using a VR system that supports both fully -immersive experiences (e.g., HMD) and non-immersive experiences (e.g., projector screen), combined with hand sketching.

2. STUDY DESIGN

In order to better understand how client representatives and architects interpret the impact of fully immersive VR and how it influences them towards becoming more receptive or reluctant towards using it, two (2) real-world projects were evaluated. The study follows a qualitative approach with data collected by means of observations, video recordings and semi-structured interviews.

2.1 Case study

The case study was based on the design of a new elementary school in the municipality of Gothenburg, Sweden, which was ongoing in different phases of the design process (e.g., spatial coordination phase, technical design) (Ostime, 2022). The project primarily used 2D drawings and incentive to use VR came from the clients when it was recognized that 2D drawings and illustrated rendered still images used by the architect could not provide a sufficient level of spatial understanding in the client group. Background information regarding the case study have been analyzed based on the following criteria: 1) purpose of using VR for design review, 2) participants' expectations prior and after each workshop as well as 3) outcome from having used VR in each of the workshops and how this influenced clients' and architects' stance on using VR. The case consisted of three workshop sessions in the following phases of the design process: preparation and brief, conceptual design stage and spatial coordination phase (Ostime, 2022).

2.2 Participants

To achieve sample representativeness, interviewees were selected based on the following criteria: 1) role in the design process, 2) prior experience of design reviews with traditional visual and information medias (e.g., 2D drawings, 3D models, physical mock-up rooms), and 3) involvement in ongoing projects for design of schools.

Whilst the focus of this study was on the same 2 client representatives and 2 architects who participated in all three VR workshops, a total of 7 other participants were also interviewed. These were the interior architect connected to the case study as well as 6 exterior architects who all had participated in separate school projects together with the client representatives interviewed in this study. The projects in which these 6 exterior architects had been involved in, involved using HMD VR for both informative- (i.e., feedback from client not incorporated into the design) and design review purposes.

It is also important to note that all participants in the studied case had prior experience of design review with 2D drawings. Moreover, all the client representatives in the studied case had experience of design review with 3D models whilst the architects had limited experience of design review with 3D models. Lastly, architects (exterior and interior) who had experience with VR had only used it for informative purposes (e.g., presenting the design to clients without incorporating any feedback).

2.3 VR-system

The Virtual Collaborative Design Environment (ViCoDE), a VR-system with support for fully- and non-immersive user-interfaces was used. It consists of several VR-headsets (e.g., Oculus Rift S kits), a multitouch table that facilitates collaborative design work with immediate, real-time feedback (i.e., object manipulation) (see fig 3) as well as a projector screen that mirrors the HMD users' view inside the virtual environment. The multitouch table uses a top view to visualize the facility. Users can pan and zoom in this view using the same standard multitouch interaction features found in most smartphones.

BIM-based components (e.g., loose and fixed furniture) are available via an asset library that is accessible on user-interface on the multitouch table, which can be added to the scene by drag-and-drop. Once added, a component can be repositioned, rotated, or removed, using the multitouch interface. The changes made on the multitouch table are then instantly updated in all the other connected user-interfaces (e.g., projector screen, HMD VR).

Fig. 3: ViCoDE set up with multitouch table and projector screen (left). Client representatives and architects design review via ViCoDE during the first workshop for project B (right).

Moreover, the HMD VR user-interface allows users access to interactive features such as measurement and dimensioning with snapping, filtering and color-coding, 3D-markups, object information (BIM-properties) and 3D-labels, section planes, miniature model (1:40 scale of the building design), multi-user and associated functionality (e.g., gather, goto), and BCF snapshots. During the three workshops, at least one person from the research team was available for supervision and providing help such as showing how to navigate with the HMD VR user-interface and how to use the various available interactive features.

2.4 Data collection and analysis

2.4.1 Interviews

The 2 client representatives and 2 exterior architects who attended all three VR workshops were interviewed as well as the interior architect of the project who participated in only the first workshop session. The focus of the interview questions were based on assessing the interior and exterior architects' and client representatives' views on 1) expectations before each respective workshop, 2) how VR influenced the dialogue of design review and how different interactive features were used to resolve design issues and 3) reflection after each workshop session.

Beyond the five interviews conducted with the 2 exterior architects, 1 interior architect and 2 client representatives involved in the project, an additional eight semi-structured interviews were also conducted with architects and client representatives who were not part of the case study but had collaborated with the same client representatives of the case study, on different projects. The purpose of these additional interviews was to gain a broader perspective on the client representatives' preferences and working dynamics between architects and client representatives when HMD VR is used for design review purposes. The assumption was that insights from individuals who had collaborated with the same client representatives on different projects could offer valuable comparative insights into preferences for information and visualization medium as well as decision-making processes when VR is used for design review.

These additional interviewees consisted of 6 exterior architects and 2 client representatives. The architects' experience of using HMD VR were mostly limited to informative purposes (i.e., presenting the building design without incorporating any feedback) and using HMD VR for design review purposes only during single VR workshop sessions. These architects were asked about 1) their expectation before and after the single VR-workshop session and 2) what challenges they consider as necessary to address in order to increase the use of VR for design review purposes. The 2 client representatives had used HMD VR for both informative and design review purposes were also interviewed and were asked about 1) their expectation before and after the single VR-workshop session and 2) how use of HMD VR helped them assess design issues and provide feedback to architects during design review.

2.4.2 Video recordings

The case with its three workshops were video recorded, with a GoPro 360 camera for a total of 3h, with 45 minutes from each workshop being selected. The two stationary GoPro 360 cameras were placed in elevated positions to capture the participants' collaboration, movement, and use of the different user-interfaces (e.g., multitouch-table, HMD VR) in the workshop room. The collected corpus of video data was transcribed for further analysis and later compared with the field notes and interview data.

The video data were analyzed by looking at the interactions between client representatives and the architects when resolving design issues as well as how both client representatives and architects each respectively interacted with the fully- (HMD VR) and non-immersive (i.e., projector screen and multitouch table) user-interfaces of ViCoDE. The verbal interaction between the participants was transcribed by one of the researchers. Segments of recording were selected based on when the greatest number of interactions took place between participants and the different user-interfaces of the VR-system in order to achieve sample representatives of captured data.

2.4.3 Analysis of interaction pattern

From the selected 45 min of video recordings of each workshop, 15 min were selected to analyze the interaction patterns between architects and client representatives and how both these type of stakeholders interacted with the fully- and non-immersive user-interfaces of ViCoDE. The selected time period for analysis of interaction patterns was based on 1) identifying parts of the selected video recordings where the architects and client representatives interacted the most with each other to resolve design issues, 2) interacted the most with the different user-interfaces, 3) specific moments where key design decisions were made (e.g., reaching consensus on design issues based on the design review agenda) and 4) number of user-interfaces that were used to resolve specific design issues (e.g., revising different room layouts on the multitouch table and validating these via HMD VR and projector screen).

These interactions are divided into three different groups:

- Group: statements, callouts and interactions not directed to a specific individual, but more to the whole group.
- Incoming: interactions directed to the person in question, such as a direct question and a request on the design
- Initiated: interaction initiated by the person in question. This includes questions directed to other person initiated by this particular person.

From the 15 min of each workshop that was video recorded, analysis was performed to count how many times the available user-interfaces – HMD, multitouch table, projector screen – were used by the different participants. These transcribed interactions were used to generate interaction graphs per workshop session with the different types of interaction documented in Microsoft Excel. The transcribed interactions were then imported to create a social network matrix using Gephi 0.10.1 to visualize these patterns emerging between users and the user-interface that they used (Bastian et al., 2009). The network comprises of nodes, representing participants in the different workshop as well as the available user-interface. The edges connecting the nodes are interactions between participants or participants and user-interfaces. Moreover, these edges are weighted by the amount of interaction occurring between the nodes, with distance and a bolder type of line indicating a stronger connection. Strong interconnection between participants/user-interfaces can be viewed in a cluster of nodes close to each other in the network as well. Lastly, the graphical layout algorithm selected for the social network is Fruchterman & Reingold layout algorithm (Fruchterman & Reingold, 1991), due to how it presents a good visualization of the interaction distribution.

3. RESULT

Based on the data analysis, six different visual interaction network graphs are presented, with two from each workshop showing the interaction between participants as well as the interaction participants had with the different user-interfaces of the VR-system. These graphs are presented together with the data captured in the semi-structured interviews as well as the video recordings. This was done to better understand how the use of the different user-interfaces of the ViCoDE system, used by the architects and client representatives, changed over the three VR workshop sessions.

3.1 Case study

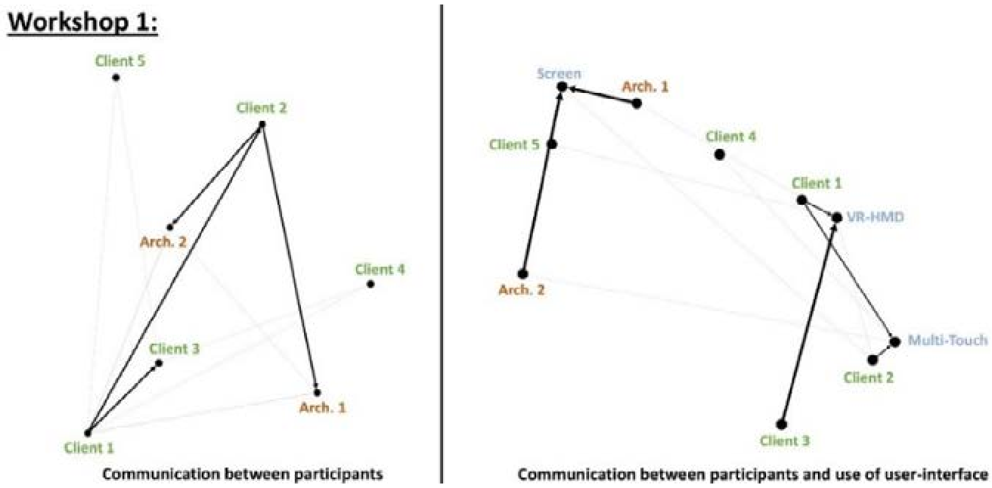

Fig. 4: Architects were noticeably receiving questions about the design from client representatives. Conversely, client representatives coordinated decision-making among themselves and used the HMD and multitouch table.

As illustrated by the edges of the nodes above the architects only used HMD VR once and instead used the non-immersive projector screen when viewing the virtual environment. Still, interesting to note is that when wearing HMD VR, design issues identified by client representatives were reviewed by architect 1 using the mark-up feature to assess the questions client 1 and 2 were asking. Rather than using HMD VR, both architects opted to view the projector screen, which displayed the perspective of HMD VR users, i.e., the virtual environment. Additionally, for a few minutes they used the multitouch table for discussing ideas and thoughts about the design. By seeing client representatives' view from inside the virtual environment, architects directed the client representatives to different points in the building design. The architects' non-immersive experience of the virtual environment via the projector screen was similarly observed in workshop 2 as well, with their fully-immersive (i.e., use of HMD VR) experience being limited to a few minutes during workshop 1.

From the client representative perspective, the multitouch table was the main user-interface used during the first workshop. This was done to resolve design issues in spaces such as classrooms to identify design issues related to hidden sightlines and furnishment. Specifically, by using interactive features such as object manipulation on the multitouch table and multi-scale in the HMD, client representatives used these different user-interfaces of the ViCoDE system to implement a scenario-based approach during design review. For instance, when changing the furnishment layout and placement of walls and windows on the multitouch table, client 1 and 2 viewed in real-time via the HMDs that there were insufficient space which would prevent teachers from performing their daily work tasks (see fig 5).

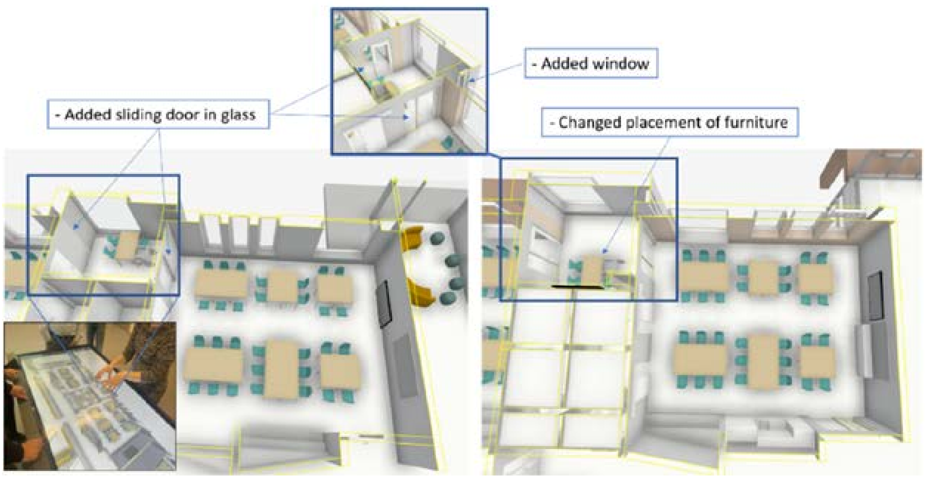

Fig. 5: Design issues identified and resolved in the first workshop via the multitouch table and HMD user-interface (left), which then were incorporated into the second workshop (right).

In the context of identifying design issues such as a lack of sufficient space, client representatives 1 and 2 who had experience interpretating 2D drawings, highlighted the difficulties with correctly assessing the design via 2D drawings. Explaining in the interview after the third workshop how "*regardless of our experience, there is a tendency for us to miss design issues when using 2D drawings [Client representative 1]"* but also *"difficulties with understanding the volume of object, such as loose furnishment, the room space itself or window elevation [Client representative 2]"*. This statement by the client representatives, however, contrasts those of the architects who shared in the interviews that they believed that *"client representatives experienced with interpretation of 2D drawings have sufficient understanding for assessing the building design correctly [Architect 1]"*. This belief among the architects could be explained by their previous experience of having worked with the same client representative when 2D drawings were used.

From the architects' perspective, the multitouch table was increasingly used in all three workshops. Even though HMD VR was not worn for more than a few minutes by either architect, with one of them explaining the reason being that *"that we already know how to visualize the virtual environment in our heads by spatial reasoning, as we have been trained by practice… [architect 1]"*, the multitouch table was the user-interface the architects interacted the most with. For example, whilst client representatives used all the different ViCoDE user-interfaces to identify and resolve design issues in the first workshop, the architects instead viewed the projector screen to discuss design issues with the client representatives. Then in the second workshop, both architects started to use the multitouch table more, as a result of helping client representatives who were unable to resolve design issues by themselves. Lastly, during the third workshop, they took the initiative to use the multitouch table and actively started to lead the discussions and in particular design issues related to building code requirements (see fig 6).

Fig. 6: Workshop 1-3. Architects directing client representatives (left) and discussing ideas with them whilst sketching (center), to directly using and reviewing the design via the multitouch table (right).

With none of the architects having used VR for design review purposes and only for informative purposes, the progressive interaction with the multitouch table indicated a certain acceptance among the architects. They used it for task-based scenarios, which could be shown and explored in VR (see fig 5 and 6).

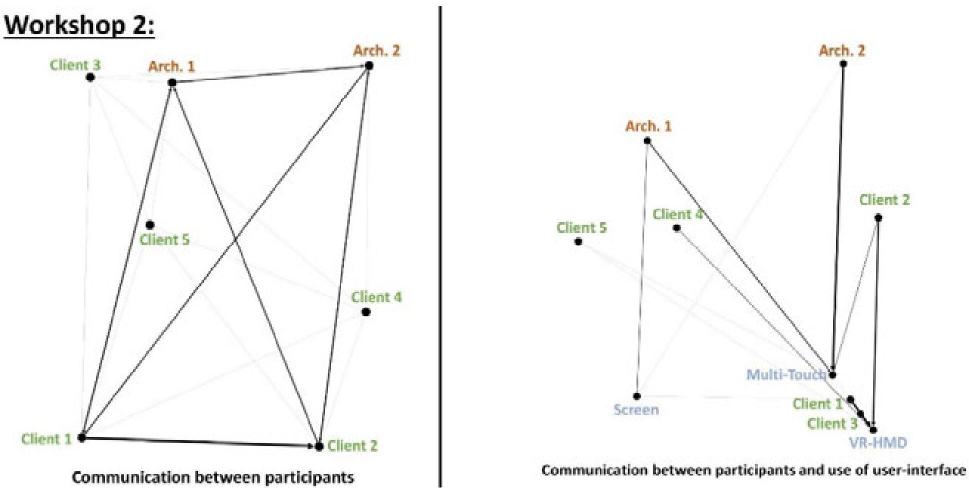

Fig. 7: Client representative 1 and 2 who participated in all three workshops had frequent interaction with each other (left). Both architects also became more involved via their use of the multitouch table (right).

As shown by the node cluster in Fig. 7 (right), client representatives continued using the multitouch table in combination with the HMD VR to rapidly review design revisions via task-based scenarios. Moreover, as indicated by Fig. 7 (left), both architects started to interact more with the rest of the participants as well as starting to primarily use the multitouch table instead of observing the virtual environment via the projector screen. In this context, video recordings show how both architects first sketched ideas on how certain room design layouts for different classrooms could be arranged (see fig 5 and 6). Following this sketching procedure, the object manipulation feature of the multitouch table would be used to validate the feasibility of the design based on these sketches. Lastly, after having decided upon different layouts, the architects would view the projector screen in combination with client representatives using HMD VR to discuss thoughts and ideas about the design together with the client representatives.

In workshop 2, the architects began using multitouch table and became more engaged in the design review process. Similarly to workshop 1, client representatives worked independently during design reviews, separate from the architects. In the context of resolved design issues, video recordings show how the first and second workshop focused on spatial zone relationships, hidden sightlines and furnishment of classrooms and different spaces. Once these design issues had been identified and resolved, 2D drawings were used alongside the multitouch table by both client representatives and architects. With the use of 2D drawings, the architects took a more active role during the design review and specifically the decision-making related to review of building code requirements.

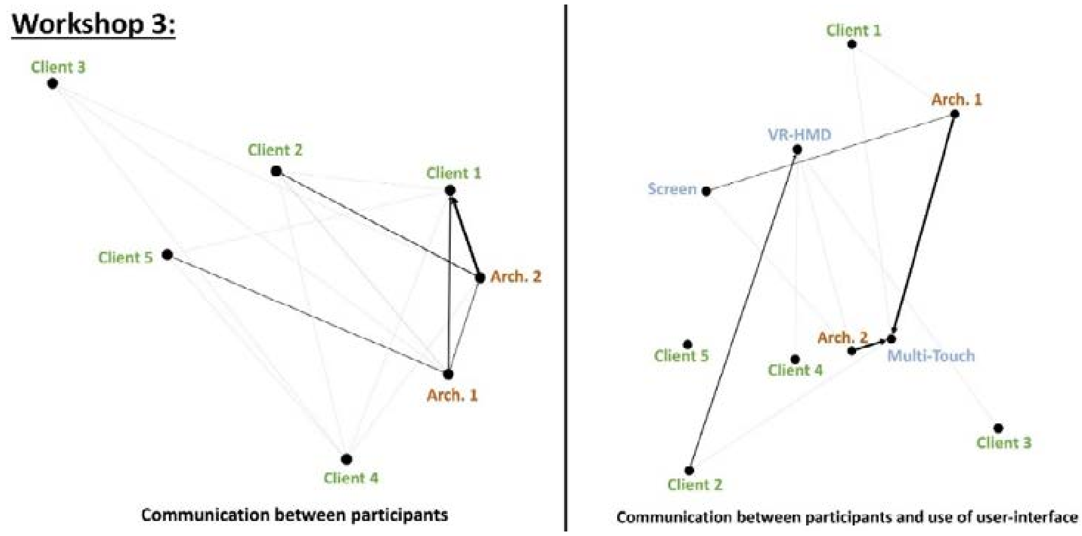

Fig. 8: Contrasting the first workshop, architects initiated more interactions with client representatives (left) as well as interacted more with the multitouch table (right). Clients had similar trend in their interactions as before.

As illustrated by Fig. 8, workshop 3 resulted in a shift in interactions from workshop 1. Specifically, during workshop 1, client representatives led the decision-making regarding the design and during this process used both the non-immersive (i.e., projector screen) and fully-immersive (i.e., HMD VR) user-interfaces of the ViCoDE system. This lead of the decision-making process by the client representatives differed from the 3rd workshop. Instead of being on the receiving end of decision-making, architects now initiated interactions with the different client representatives.

One explanation for the shift in decision-making could be based on the architects being unfamiliar with how to use VR-systems such as ViCoDE for design review, but slowly during three workshops grew more accustomed to the different user-interfaces. Another explanation is that after addressing design issues concerning spatial understanding of the building design, the architects took the lead in interactions and decision-making when reviewing the building code requirements, similar to a traditional design process involving 2D drawings. Connected to the last explanation, another possibility for the shift in decision-making could be that initially when client representatives were using the different user-interfaces of the VR-system, the architects were unsure on their "role" during design review with a VR-system such as ViCoDE. Specifically, whilst the video recordings show how the architects initiated interaction and discussions during the last workshop, the design review were mainly facilitated by the client representatives themselves. With client representatives doing design review mostly independent from the architect in the first two workshops, the role of the architects in these sessions was questioned, as evident by the incoming interactions shown in Fig. 4 but also as the video recordings show when the client representatives questioned design issues they previously were unable to identify during design review with 2D drawings. Moreover, this challenge of the architects' role in the design process was also pointed out in the interview with the interior architect involved in the project:

"When using VR for design review purposes, I sense that end-users such as client representatives identify design issues before we (architects) do and following this, ask questions about the design that we usually are the first to ask whenever 2D drawings and 3D models are used. [interior architect]"

Whilst the architects' lack of experience in using VR for design review purposes explains this statement, it could also explain client representatives' receptiveness towards using the VR-system from the very first workshop. For example, whilst the architects were initially reluctant to interact with the multitouch table, client representatives actively and continuously used all user-interfaces of the VR-system and in particular, the different interactive features of both the multitouch and HMD VR.

In general, results for all the three workshops showed client representatives and architects being receptive towards using many of the same user-interfaces of the VR-system. Whilst similarities in interaction towards using the multitouch table were apparent, equally apparent was the contrast in reluctance and receptiveness in using the HMD VR. From the architects perspective, they became more receptive towards use of interactive features such as object manipulation throughout the three workshop sessions. Specifically, by first sketching with pen and paper and then testing these different layouts on the screen showed how the architect initially started with directing client representatives via the projector screen to later in the second and third workshop actively being part of the discussions that took place. From the client representative perspective, receptiveness to both the non-immersive user-interfaces (i.e., multitouch table and projector screen) and the fully-immersive one (i.e., HMD VR) led to a decision-making process mostly independent of the architect. Moreover, this independence shifted in the second and in particular the third session when design issues related to building code requirements (e.g., daylight, distance between spatial zones) were reviewed. When reviewing these requirements, the architect was more receptive than the client representatives in using the multitouch table and with both type of participants showing reluctance towards using the HMD VR when reviewing building code requirements.

4. DISCUSSION

4.1 Participants' interaction with user-interfaces of a VR-system

Findings show that the different user-interfaces of the ViCoDE VR-system were used to varying degrees during the three workshops. On the one hand, client representatives from the first workshop all through the third session, interacted mainly with the HMD VR and multitouch table as well as the projector screen. On the other hand, the architects' reluctance to use HMD VR for design review persisted throughout all three sessions. Yet, both client representatives and architects frequently used the multitouch table.

From the client representatives' perspective, different interpretations can be made as to why their interactions with the different user-interfaces were consistent. Firstly, with mainly HMD VR increasing their spatial understanding compared to 2D drawings (Chowdhury & Schnabel, 2020) client representatives were able from the first workshop to identify and resolve design issues that they previously unaware of. This unawareness of design issues, regardless of previous experience with interpretation of 2D drawings, could also be interpreted as the client representatives being more receptive towards using the different user-interfaces of the ViCoDE system and in particular HMD VR. This could be due to HMD being perceived as a more engaging information and visualization medium than 2D drawings (Johansson, 2016) with the ego-centric frame of reference client representatives had via HMD VR (Paes et al., 2023), helped them better assess different furnished layouts in workshop 1 and 2. Moreover, the design changes made in the 1st workshop with HMD VR and multitouch table and later incorporated in the 2nd workshop, can be interpreted as client representatives being provided with clearer visual cues (e.g., size of room, placement of windows) (Hermund et al., 2017) when perceiving volumetric qualities of the building design better in fully-immersed virtual environment (Chowdhury & Schnabel, 2020). Secondly, it could be argued that by identifying design issues such as hidden sightlines, furnishment and design of different spaces (i.e., workshop 1 and 2) via HMD VR, client representatives grew more receptive towards continued interaction with HMD VR but also the multitouch table. Thirdly, by adopting task-based scenarios during design review (i.e., workshop 1 and 2), it can be argued that collaborative practices such as Co-design further helped facilitate their interaction with HMD VR and the ViCoDE system at large (Roupé et al., 2020). Also, as observed during workshop 1 and 2, client representatives made design changes such as furnishment and revision to layout of different spaces independently from the architects. This independence is further acknowledged by the project's interior architect when she explains how clients tend to identify and ask questions about the design in HMD VR before the architects do. This suggests that Co-design is more likely to emerge when VR-systems with support for both HMD VR and object manipulation are used during design review, as client representatives become part of the design team (Caixeta et al., 2019).

From the architects' perspective, it is interesting to notice, due to how VR being described primarily as a presentation tool used by architects (Achten, 2021; Scheer, 2014), that interaction with different user-interfaces in the different workshops, was mostly limited to the non-immersive experience, offered by the projector screen and the multitouch table. By viewing client representatives' HMD VR view of the virtual environment and using the projector screen to direct them in the building design, the architects' experience of the virtual environment was limited to a non-immersive one. In this context, when using sketching with pen and paper prior to testing the idea on the multitouch table, we saw that the architects are more receptive towards interacting with user-interfaces they perceive as familiar with their own traditional design tools (e.g., multitouch touch table with top-view similar to 2D drawings) (Scheer, 2014), rather than user-interfaces they do not have experience in using for design review purposes (i.e., HMD VR). This familiarity could be argued to be based on the top view perspective they are used to work with (e.g., 2D drawings) but also for how the use of interactive features such as object manipulation allowed them to seamlessly test and validate design proposals when swapping between sketching and multitouch table. This idea of familiarity could also explain why architect 1 in the first workshop, on their own accord, used the mark-up tool to better understand the client representatives' question on the design. To this point, it can be interesting for future studies to investigate whether architects design review in multi-user HMD VR, together with client representatives, would affect their resistance towards engagement with HMD VR. For instance, what interactive features would be needed in HMD VR to result in a shift for architects viewing HMD VR primarily as a presentation tool (Scheer, 2014), to one of their primarily chosen mediums used for design review?

4.2 Communication between participants when using VR-systems

Results from the three workshops suggest that VR-systems with support for multiple user-interfaces and available interactive features enable client representatives to have a Co-design approach to design review. With the architects being questioned on their decisions made earlier with 2D drawings (workshop 1 and 2), we could see that in conjunction with client representatives doing design review independently, that their role in the design review context came into question. With the third workshop instead consisting of architects initiating interactions with the client representatives as well as leading the design review when reviewing compliance with building code requirements via 2D drawings, the questioning of architects' hierarchical position is supported (Cruickshank et al., 2013; Scheer, 2014). Also, with the explanation provided by the interior architect on how design issues and questions on the design are now instead initiated by client representatives rather than the architect, it can be argued that the role of architects during design review with VR, needs to be further explored to address their resistance toward engaging with HMD VR.

Consequently, providing client representatives with the conditions to express their needs about the design (e.g., use of interactive features to enable design review via task-based scenarios) results in increased sense of ownership of decision-making. Nevertheless, with architects experiencing a loss of decision-making power (i.e., workshop 1 and 2) (Maftei et al., 2018), we saw that VR used for design review purposes would be useful in collaborative practices such as Co-design. In this context of Co-design, it is noteworthy how the architects in all three workshops started developing solutions to different design issues firstly via non-immersive design tools, i.e., sketching by hand, and then shifted over to the non-immersive user-interfaces of ViCoDE, i.e., multitouch table and projector screen. Whilst this hybrid design environment with both non-immersive and immersive user-interfaces can help involved participants to immediately validate their design decisions (Okeil, 2010), it could be argued that the design creation/feedback/revision cycle between architects and client representatives would be more efficient if alternation between non-immersive (i.e., projector screen and multitouch table) and fully-immersive (i.e., HMD VR) environments was not required. With architects developing and revising their design ideas in a fully-immersive environment, they would also likely face a loss of predictability in their working methods (Cruickshank et al., 2013) and decision-making on the design (Scheer, 2014). As such, the "loss" of predictability in working methods and decision-making power could make architects in the fully-immersive virtual environment susceptible to being wrong about certain design ideas, i.e., how the needs and wants of the building occupants are considered in the design.

Therefore, by immediately facing the consequences of their design ideas via use of task-based scenarios (Nikolić & Whyte, 2021; Roupé et al., 2020), it is more likely that the typical hierarchical position of the architect (Scheer, 2014) is questioned, due to client representatives identifying and resolving design issues independently from the architect, as evident by 1st and 2nd workshop. Although the setting of the workshops involved participants using both a non- and fully-immersive approach to design review, it could be argued that the questioning of the architects decisions of the design would be further reinforced when the design review with involved participants is mainly done in a fully-immersive environment. As a result, it is important to explore the conditions architects need, to design review in fully-immersive VR. For instance, how would availability of object manipulation in HMD VR influence collaboration between architects and client representatives? Would collaborative practices such as Co-design more likely be facilitated with everyone doing design review in the virtual environment? Connected to the last point and as evident by the video recordings from workshop 1 and 2, the VR-system tested in this study, i.e., ViCoDE, meant that 2 out of 3 design review sessions were observed to be an isolating experience for the architects. This isolating experience meant that the architect's typical role of a facilitator (Scheer, 2014), were not as apparent as in design processes involving traditional design medias (e.g., 2D drawings and 3D models). It would be of interest to further study what type of role, whether similar or a new one, architects need to take on when doing design review with fully-immersive VR (Maftei et al., 2018). Thus, these are just some of the questions worth exploring in future studies, to better understand the resistance to engagement with VR-systems.

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COLLABORATIVE SITE LAYOUT PLANNING USING MULTI-TOUCH TABLE AND IMMERSIVE VR

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ABSTRACT: *Building Information Modeling (BIM) is changing the way architects and engineers produce and deliver design results, and object-oriented 3D models are now starting to replace traditional 2D drawings during the construction phase. This allows for a number of applications to increase efficiency, such as quantity take-off, cost-estimation, and planning, but it also supports better communication and increased understanding at the construction site by means of detailed 3D models together with various visualization techniques. However, even in projects with a fully BIM-based design, there is one remaining part that is still done primarily using 2D drawings and sketches – the construction site layout plan. In addition to not take advantage of the benefits offered by 3D, it also makes it difficult to integrate site layout planning within the openBIM ecosystem. In this paper we present the design and evaluation of a user-friendly, IFC-compatible software system that supports collaborative, multi-user creation of construction site layout plans using both multi-touch table and immersive VR. By allowing temporary structures, machines, and other components to be easily added and updated it is possible to continuously produce and communicate 3D site layout plans that are aligned with the schedule and supports integration with other BIM-tools.*

KEYWORDS: *BIM, VIRTUAL REALITY, VR, OPENBIM, IFC.*

1. INTRODUCTION AND BACKGROUND

With increased focus on digitalization and efficiency within the Architecture, Engineering, and Construction (AEC) industries, detailed Building Information Models (BIM) from the design are now often available for use by the contractor. This can facilitate the tendering process and make cost estimation and planning more efficient, but above all it supports enhanced communication and understanding during the production phase in the form of detailed 3D models with corresponding metadata. Furthermore, already today there are examples of so-called *"drawingless"* projects such as Röforsbron, Slussen, and Celsius, which clearly shows that the industry is moving more and more towards a situation where traditional 2D drawings are given less space (Cousins, 2017; Johansson & Roupé, 2019). In fact, in Scandinavia, Total BIM has emerged as a concept where the BIM is the legally binding construction document and no traditional 2D drawings are delivered to the construction site (Disney et al 2022). However, there is still one document that the contractors themselves have to create and keep up to date – *the construction site layout plan*.

Currently, the site layout plan is often drawn up in 2D by default – often using Bluebeam – and although the work differs between projects, there are several recurring problems connected to it (Andersson et al., 2019). Gros (2019) investigated the work with site layout plans at one of Scandinavia's largest contractor and found that:

- Even if all of the design is done using BIM, the site plan is still usually in 2D
- Typically just one person working with the site plan
- The site plan is rarely updated and often differs from reality
- The work with the site plan is often linked to lack of time and stress
- Often poor communication and respect for the site plan (difficult to interpret plans)

However, there are also several good examples in practice which have shown the possibilities of working with site layout plans in 3D, often created and maintained in SketchUp (Jongeling, 2013). 3D offers many benefits regarding elevations and general workplace organization in the vertical dimension, at the same time as it is easier communicate and present ideas around it. Still, this approach typically requires a modeling expert responsible for updating the plan, and in the end these plans tend to be exported as static 2D images instead of being integrated with other BIM datasets (Gros, 2019).

Going beyond site layout planning in real-world projects, much research has focused on turning site layout planning into an optimization problem that can be automated, which – in many ways – is similar to using probabilistic and generative methods for automated creation of production plans and schedules (Taghaddos et al., 2021; Abune'Meh et al., 2016; Kumar and Cheng, 2015; Isaac and Shimanovich, 2021; Fischer et al., 2018). At

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Mikael Johansson, Mattias Roupé, Mikael Viklund Tallgren, *Collaborative Site Layout Planning Using Multi-Touch Table and Immersive VR,* pp. 81-90, DOI 10.36253/979-12-215-0289-3.08

the same time, there is also research that emphasizes the benefits of collaboration, teambuilding, and commitment, and instead advocate more focus on user-friendly software tools and various visualization techniques, for instance Virtual Reality (VR), to support the collaborative planning work (Tallgren et al., 2021, Tallgren et al., 2020). VR, in particular, can clarify aspects of the design that are difficult to comprehend from traditional 2D documents, and can better resemble real work environments – features that are useful when evaluating planning scenarios and reviewing constructability (Zaker and Coloma, 2018; Wolfartsberger, 2019). Given these properties, it is therefore logical that the use of VR has been tested also for site layout planning (Xu et al., 2020; Muhammad et al., 2019). In this context, and when compared to traditional 2D methods, VR has been shown to make the plan more effective to comprehend and to enhance the ability to detect clashes (Muhammad et al., 2019). Nevertheless, certain aspects of the layout planning are still considered to be more efficient in 2D, which tells us that instead of trying to choose between either one of these interfaces it would perhaps make more sense to try and combine them, which has been a successful approach for both urban planning and collaborative healthcare design (Faliu et al., 2019; Roupé et al., 2020). In this paper we take inspiration from these ideas and present the design and evaluation of a multi-user, multimodal system for collaborative creation of site layout plans. The system combines multi-touch table and immersive VR, but contrary to similar approaches within urban planning and healthcare design much more focus has been put on integration within the openBIM ecosystem.

2. THE COLLABORATIVE SITE LAYOUT PLANNING ENVIRONMENT

To support a multi-user, multimodal planning environment we have used BIMXplorer and further customized it. BIMXplorer is a real-time desktop- and VR-viewer that directly supports the IFC file format and creation of federated building models (Johansson, 2016; BIMXplorer, 2023). IFC import is implemented using the xBIM framework (Lockley et al., 2017), and by taking advantage of efficient occlusion culling, BIMXplorer allows large and complex BIMs to be visualized in immersive VR without the need to simplify or decimate the input dataset. The VR user interface – explained in detail in (Johansson and Roupé, 2022) – consists of a tools palette with support for sectioning, measurement, filtering, markups, BCFs, and multi-user sessions (Fig 1). In the following subsections we further describe the multi-touch as well as VR interface that were developed to support user-friendly, collaborative creation of site layout plans. Fig 2 presents an overview of the new system using a sample configuration with both co-located and remote clients.

Fig. 1: Examples of different tools and models in BIMXplorer.

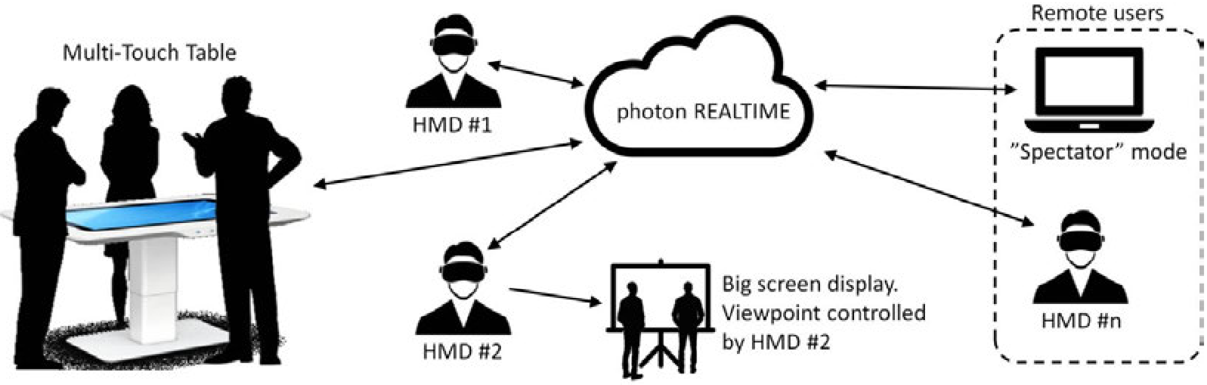

Fig. 2: System overview using a sample configuration.

2.1 Prefab database creation

Site layout planning in 3D mainly consists of placing 3D-objects that represents temporary structures, machines, and temporary placements for materials as instances in a 3D-environment. We refer to these objects as prefabs, and the motivation around the creation and organization steps was to allow easy creation from already present 3D-models or BIMs. We therefore implemented support for also importing .skp- and .fbx-files using their respective APIs, and then simply implemented a tool in BIMXplorer to select and save a single or multiple objects as a prefab, with the current view as the preview images (Fig 3, middle). Depending on the type of component it also makes sense to be able to select the center of rotation (i.e. during planning), which is why we optionally support placement of a pivot point using a standard translation gizmo. Finally, with a number of prefabs created, a user can then organize and group the prefabs in different folders and subfolder (Fig 3, right) before selecting a root-folder, which will then import and create a prefab database file (.pfd-file), which will have the same organizing structure. Assuming a very large number of prefabs are originally created, this makes it possible to select a subset for a certain planning workshop, like a template. The whole procedure is illustrated in Fig 3, where a SketchUp scene is first imported (left), followed by selection and isolation of a skip container that is save as a prefab (middle), and finally the folder structure where it is saved (right). Note however that this only has to be done once, to create a pfd-file, which can then be re-used as a template in several planning workshops.

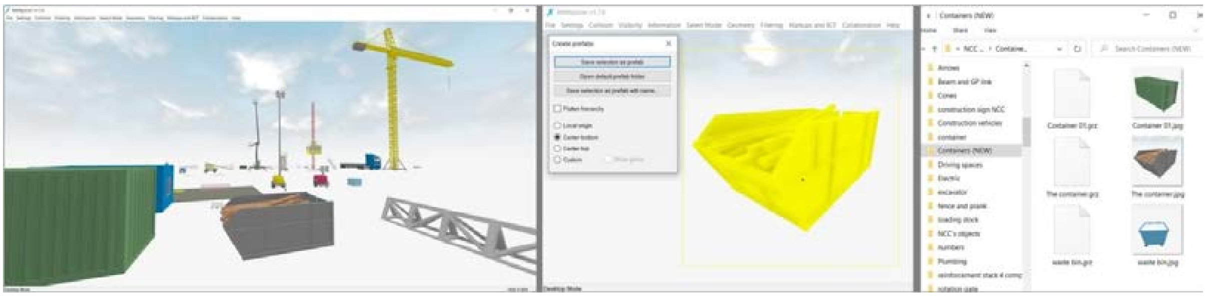

Fig. 3: The prefab creation process in BIMXplorer and file structure.

2.2 Desktop UI and touch interface

The desktop, multi-touch interface is inspired by our previous work for healthcare environment design (Roupé et al., 2020), but implemented on top of BIMXplorer and much more adopted for use in a openBIM ecosystem. The touch interaction is a custom implementation using "raw" touch events in Windows, i.e. listening to WM_TOUCH events. The actual interface follows that of StreamBIM, with two-finger pan-and-zoom, one-finger for look-around in 3D as well as scrolling in menus, and one-finger tap for selection and button pressing. No inertia is used. The UI is implemented with Dear IMGUI and has a collapsible toolbar with functionality for adding objects, sectioning, visibility and filtering, settings, and file I/O. As seen in Fig 4, sectioning is done by selecting a level/floor from IFC-data and can then be adjusted up or down. With BIMXplorer already using Dear IMGUI for the tools palette in VR, it was possible to directly re-use certain UI-element, such as for filtering and sub-model visibility. In this context, the filtering capabilities are particularly interesting as it allows for controlling visibility and colors of objects based on their properties. This makes it possible to filter out certain scenarios if the data is available in the IFC-file(s), such as subcontractor or scheduling information. For instance, if scheduling information is present, it's possible to filter out only those objects that will be constructed at a certain point in time, making site layout and logistics planning adhere to the real construction schedule.

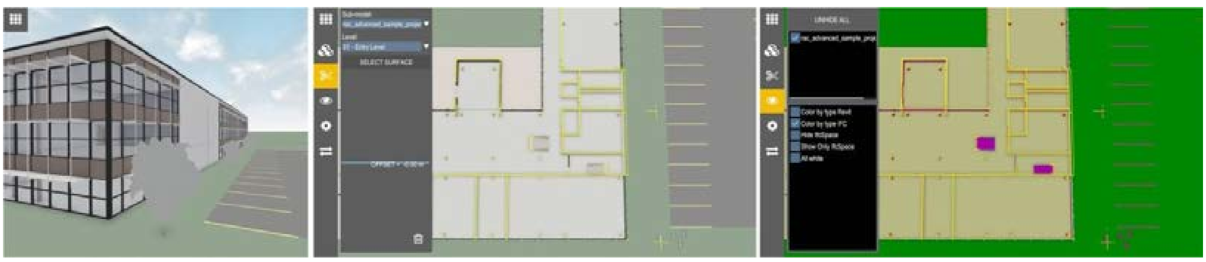

Fig. 4: The multi-touch table interface, including sectioning-by-floor, and filtering in the top-down view.

All the imported prefabs (i.e. the prefab database) are accessible in a folder structure and are added using drag-and-drop as illustrated in Fig 5. Selecting an object by tapping brings up the context menu making it possible to hide or delete the object. A selected object – or multiple selected objects – can directly be moved horizontally by dragging or rotated using the "gizmo". By toggling one of the context menu buttons, vertical movement is activated instead.

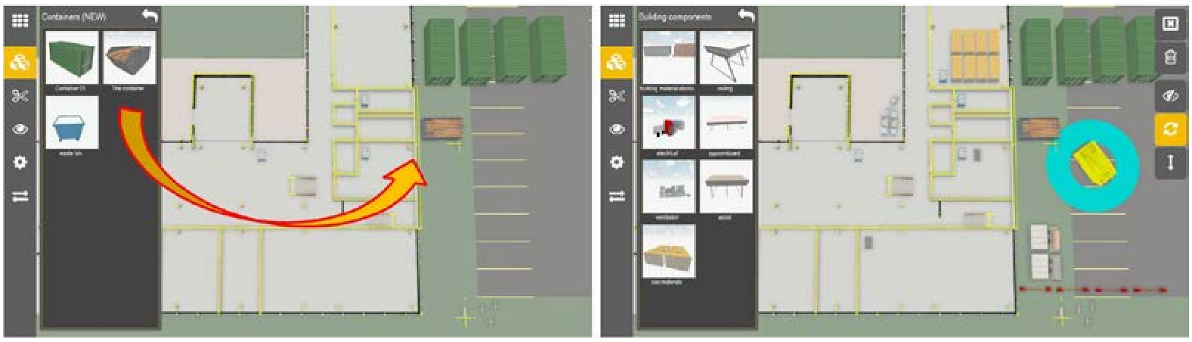

Fig. 5: Adding prefabs using drag-and-drop (left), and context menu and rotation gizmo (right)

2.3 VR interface

A similar interface for adding objects is implemented in VR as well by dragging and dropping prefabs from the tools palette, as seen in Fig 6, left. In fact, as this is done using Dear IMGUI the actual code is almost identical, which is one of the main benefits of using the same UI toolkit for both 2D desktop and immersive VR. Moving, re-placing, and rotating objects is also similar, but with gizmos more adapted for use in a pure 3D environment (as opposed to a 2D desktop interface).

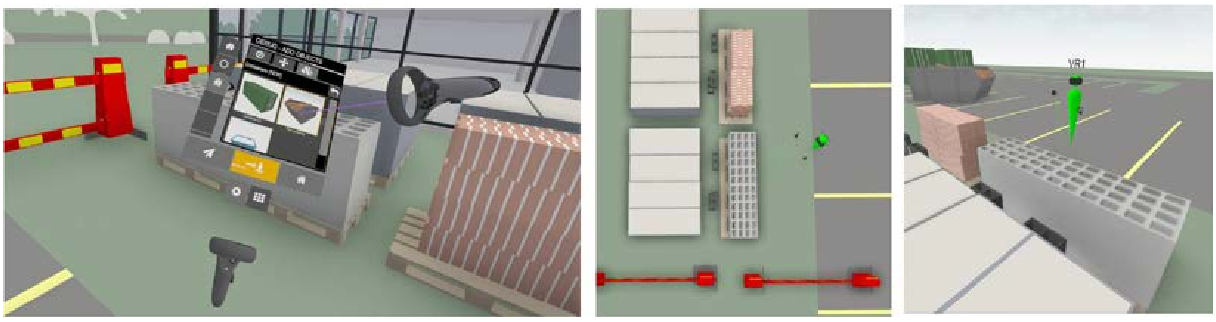

Fig. 6: Adding prefabs using drag-and-drop in VR (left), view of VR avatar in other clients (right)

2.4 Multi-user and collaborative planning

The multi-user functionality already present in BIMXplorer was extended to also support collaborative planning and adding, translation, and removal of instanced prefabs. The implementation is based on the Photon Realtime SDK and uses no other server infrastructure. All clients load the same model (.bmx-file) and prefab database (.pfd), and then call *"JoinOrCreateRoom"* (Photon API) with a previously agreed upon meeting ID. The first client that calls this function performs the actual creation of the Photon "room", and all other clients will then join it. Every modification to the shared environment, such as adding or translating objects, creating 3D-markups, or hiding/showing objects is transferred to all clients with the use of Photon events. These events use the *"SendReliable"* and *"Cached Event"* functionality in Photon to make sure that even if a client is connecting much later than the other, that client will still receive all the modification events that have already happened when joining. Position and orientation of all the clients (i.e. the avatars), on the other hand, is using *"SendUnreliable"* because it is regularly updated anyway. However, in either case, no 3D-data is ever sent over the network, just IDs and transformation matrices. The only exception is 3D markups which are represented as a polyline with 3D coordinates. Still, all clients must be able to uniquely identify objects and prefab instances even if created locally on a single client. The solution was to simply let each client generate and assign a GUID when adding or creating a new object (using *CoCreateGuid*).

2.5 IFC export and openBIM

As previously stated, one of the main challenges when considering site layout planning in a modern BIM context is the need to integrate and align different data sources, from design as well as from production. In essence, this means that we can no longer only produce images and 2D-data, but instead also needs to provide 3D-data. As the solution to consume BIM-data is through the IFC file format it thus makes sense to also use that for producing data. Fortunately, the xBIM framework that is used in BIMXplorer to import IFC-files also has functionality to create IFC-files. With the underlying geometry representation in BIMXplorer being indexed triangular meshes we have chosen to use IFC4 which has support for *"IfcTriangulatedFaceSet"*. The possible options exposed for IFC-export are everything, selected, or visible, which means that it is also possible to only export a subset of the planned components as an IFC-file. This makes it possible to separate the exported IFC-files both temporally and spatially. Furthermore, by using the BCF functionality it is possible to transfer additional information, either back to the design organization or as viewpoints or "points-of-interest" for on-site mobile communication platforms, such as Dalux or StreamBIM. Example of both IFC- and BCF-export is seen in Fig 7, where the sample layout shown in Fig 5 is exported as an IFC4 file and imported into Solibri together with two BCF viewpoints. In Fig 8 the openBIM-supported model- and dataflow is illustrated.

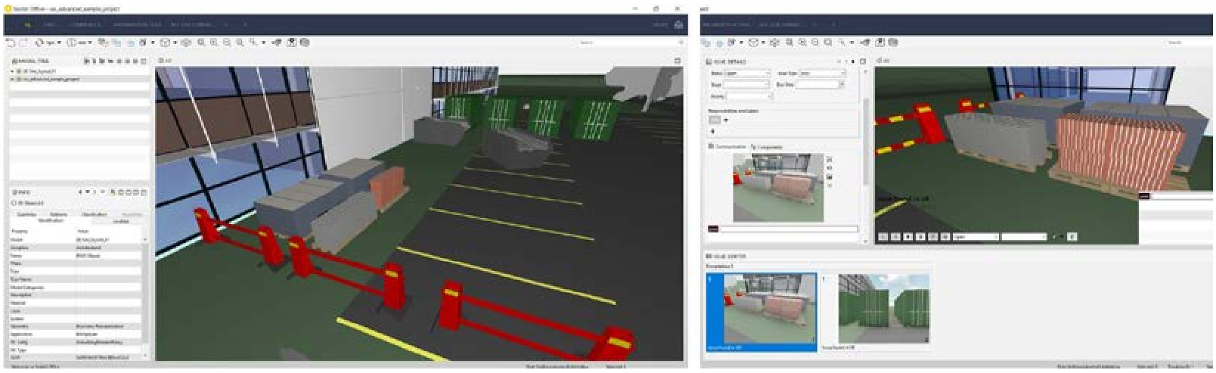

Fig. 7: The "Site component IFC" (left) and BCF (right) exported from BIMXplorer opened in Solibri.

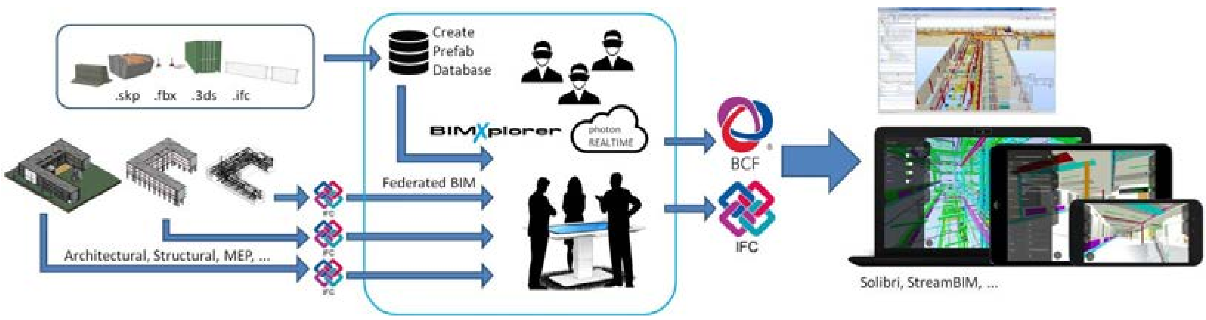

Fig. 8: Schematic illustration of the openBIM-supported 3D model- and dataflow.

3. EVALUATION

The developed system has been evaluated during a workshop session with representatives from the construction industry. The primary focus during the workshop was around safety and specifically to see if immersive VR could provide benefits in detecting hazardous situations compared to only using traditional 2D drawings. As part of that investigation the site layout planning functionality was tested and evaluated with respect to placing guardrails and temporary covers. The complete setup during the workshop can be seen in Fig 9. A single, large touch screen was used together with two VR headsets, one of them also connected to a projector. Seven (7) participants, both from design and production, took part in the exercise which lasted around three hours. The test case was the 6th floor of the Kineum project, a 27 story tall building recently constructed in Gothenburg, Sweden (Fig 10). This project was chosen due to the sheer size and complexity, but also because design documents included both BIMs and traditional 2D drawings. In the first part of the exercise the participants where ask to identify areas that can be hazardous during construction using only 2D drawings. In the second part the same was done, but this time in VR using multi-user. In the third part, safety equipment, such as guardrails and covers, was placed and updated using the site layout planning tools. However, note that the possibility of adding and moving objects in the immersive VR interface was not implemented at the time of the workshop. Still, all modifications done on the multi-touch table (add, move, delete, etc.) was updated in the VR interface. As an additional and final step, the evaluation was completed with a post-workshop interoperability test.

Fig. 9: The setup during the workshop.

Fig. 10: The Kinum project; BIM, structural-only BIM, construction, completed building (left to right).

4. RESULTS AND DISCUSSION

4.1 2D vs. VR and multi-touch table for safety review

Except for the outer perimeter, there were mainly four areas that required safety precautions; three large openings and the area around the elevator shafts. From the 2D exercise only two participants managed to identify all of them. Among the other participants there were various differences, but they all missed the triangular shaped opening, which is actually quite difficult to spot in 2D due to its somewhat uncommon shape. However, when moving on to the second part in the exercise, using VR, all areas requiring safety precautions were easily identified by all participants. On the one hand, this could be seen as an unfair comparison, considering that there were elements of collaboration with the multi-user setup. On the other hand, this was the first time using VR for four of the participants which introduce an extra layer of mental workload before navigation and interaction with the different tools are fully understood. Regardless, it was clear from the participants' response and comments that VR provided a much more immersive and true-to-scale experience that allowed all of them to easily detect all floor openings, including the one that most missed in the first part of the exercise. Still, already by inspecting the model top-down view at the touch table, openings were much easier to detect than in the 2D drawing alternative due to the 3D perspective and shading. However, VR was considered particularly valuable in complex situations that are difficult to assess through traditional methods. Furthermore, with the general understanding that every action in construction carries some level of risk to workers' safety, all participants acknowledge the unique properties of VR to understand and comprehend complex design choices from a safety and constructability perspective, thereby improving safety planning and design. Finally, in addition to simple identify the hazardous areas, the participants were also asked to use the markup tool to illustrate suitable safety measures, as seen in Fig 11.

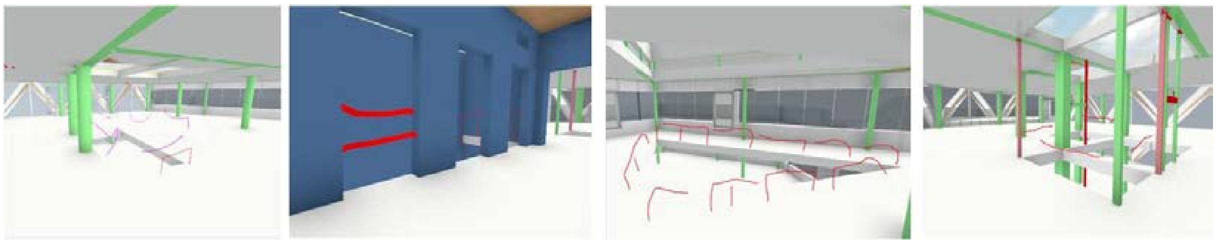

Fig. 11: Participants used the markup tool in VR to illustrate where safety measures were needed.

4.2 Planning and collaboration

In the third part, the top-down interface on the multi-touch table was used to place safety measures around the identified hazards, the results of which can be seen in Fig 12. One participant had experience from similar planning settings and specifically around the difficulties in getting people to interact with BIMs and 3D models on touch- and smartboards using desktop BIM-viewer applications and was surprised to see how easy and intuitive it was to add new components to a highly complex BIM using the multi-touch interface:

“We have always had problems in the past of getting non-experts and 'normal' people to be able to interact with these large and complex BIMs”

The main activity was around the touch-table and in that respect some participants indicated that they felt a bit isolated when immersed in VR, even if this was a multi-user session. Similar observations have been noted in previous research as well (Roupé et al., 2020; Truong et al., 2021). However, this might have been different if the functionality of adding and moving objects also in VR had been available during the workshop. Other than making markups, the VR users could only tell the other participants what to do and therefore became more of observers and reviewers, than that of creators. Still, participants around the touch-table liked that they always could see where VR viewers were. On the other hand, it was clear that immersive VR and the 1:1 scale was superior in order to understand narrow or wide space and to identify safety and constructability issues. For instance, the initially placed safety precautions for the elevator shaft section were later identified as too "light", which was not as easy to spot in the top-down desktop interface, but very obvious when seen in a first person, true-to-scale perspective. This actual combination and collaboration using multiple interaction and visualization interfaces was also identified as an efficient setting in order to increase understanding and share and exchange knowledge across professional disciplines. In particular, it was stated that the collaborative walkthrough between design and construction safety team can increase designers’ awareness and foster designer contribution for safety planning.

In addition to the request for also adding and moving components in the VR interface, there were several suggestions for improvements and also some identified issues. One suggestion that came very early during the workshop was to implement more of a polyline-drawing-tool for the guardrails, as it was found a bit inefficient and time-consuming to drag and drop all the individual sections and then place and rotate them correctly around the openings. To some degree this was also made extra cumbersome because the ray-intersection routine (i.e. hit-testing) does not use a dedicated collision shape but instead uses the actual geometry, which in the case of the guardrails consists of thin bars that are difficult to hit. The concept of a polyline drawingmode was also suggested for an area-drawing tool (i.e. surfaces). Even if 3D components are preferred as representations several participants highlighted the need to be able to also illustrate areas. Further suggestions included the possibility to group objects together to form composites and to be able to copy-paste objects (both individual and composite groups).

Fig. 12: Guardrails, temporary covers, and fences placed using the top-down interface on the multi-touch table.

4.3 Interoperability

All the safety equipment that was added to the project during the workshop was exported as a single IFC-file and then imported into both Solibri and StreamBIM together with other disciplines in the project (e.g. architectural, structural, MEP, etc.), which can be seen in Fig 13. In effect, this introduces a new discipline to the federated BIM – *Temporary Safety Components*. Although the IFC-export wasn't actually used during the workshop (i.e. it was imported into StreamBIM and Solibri at a later time), the functionality was discussed and the prospect of having an IFC-file with temporary structures and site objects as output sparked many ideas from the participants. For instance, it meant that all other tools that are part of the BIM palette, such as automatic quantity takeoffs and clash detection, could now also be used for temporary structures and components. However, regardless of future applications, the interoperability test successfully completed our initial evaluation which shows that, not only can non-designers collaboratively create construction site layout plans in 3D, but also directly integrate and use this 3D data together with all the other BIM sources received from the design organization.

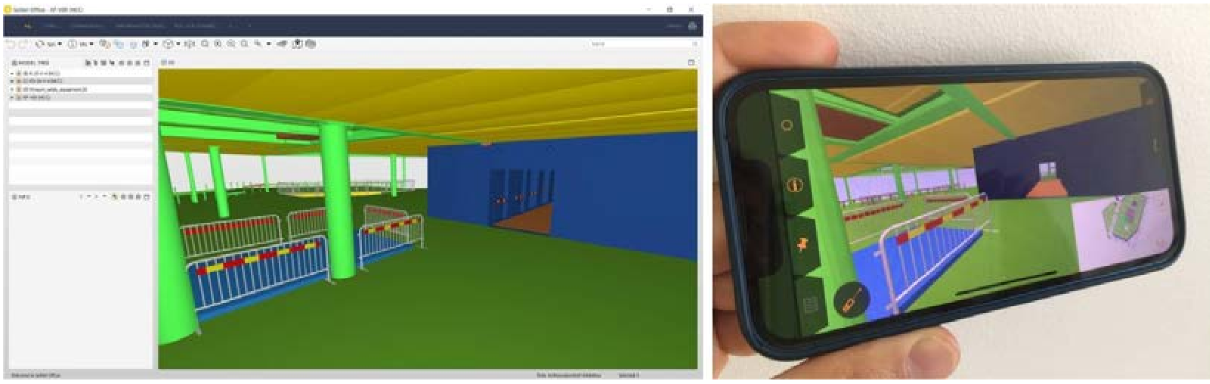

Fig. 13: The "temporary safety components" IFC-file imported into Solibri and StreamBIM.

5. CONCLUSIONS

In this paper we have present the design and technical details of a user-friendly, IFC-compatible software system that supports collaborative, multi-user creation of construction site layout plans using both multi-touch table and immersive VR. In addition we have presented an initial evaluation of this system with respect to safety review and planning and layout of temporary safety components. For the specific task of identifying hazardous situations, the presented system was found to be more efficient compared to only using traditional 2D drawings. The multiple interaction and visualization interfaces were found to complement each other and to provide an efficient environment for collaboration and knowledge sharing across different professional disciplines. In this context, the immersive VR interface was found to be superior in order for users to understand space, dimensions, and complex designs, whereas the multi-touch interface was considered very intuitive and easy to use with suitable tools for adding and modifying 3D components. With the ability to also export the planned environment as an IFC-file the system has been shown to support creation and continuous update of 3D site layout plans that can be fully integrated with a projects other BIM sources and tools.

For future work it would be interesting to implement some of the request and suggestions that were proposed during the evaluation, such as a polyline drawing tool for guardrails and grouping of components. Furthermore, it would be interesting to explore and evaluate the system with a more dedicated focus on all aspects of construction site layout planning, not only safety.

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APPLICATION OF SMART TECHNOLOGIES FOR ASSESSING USERS' WELL-BEING FOR IMMERSIVE DESIGN STRATEGIES: A STATE-OF-THE-ART REVIEW

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ABSTRACT: *As never before, during the COVID-19 pandemic, the effectiveness of the digital design strategies on the user's well-being has been questioned. However, a research branch astride digital design and neuroscience able to overcome net discipline borders to analyse users' well-being seems to be lacking. Today mainly qualitative data are used in the design field for the investigation of users' quality experience. Although fundamental, they also have great disadvantages such as unanswered questions, unconscientious responses, and respondents' biases. As such, a systematic state of art review is presented to find methodologies and tools currently used in medicine to identify the impact of digital design strategies (XR) on users' well-being through quantitative and objective data. The main technologies used for this purpose have been synthesized in a schematic chart by reporting the principal related biometric data (skin conductivity, heart rate metrics and breathing rates), as well as other technologies such as video/images/audio analysis based on sensors and machine learning to reach out mass numbers. In conclusion, gaps and future applications of this innovative approach within the virtual environment have been identified by the authors.*

KEYWORDS: *extended reality, virtual reality, neuro-design, digital design, immersive experience, user experience, well-being assessment*

1. INTRODUCTION

In these current times and especially within the COVID-19 frame, we are witnessing design calling itself under question by focusing on the redefinition of the relationship between users and spaces. Although the importance of quality space has been considered a central point in design planning, the current pandemic is indeed pointing out a global dissatisfaction in this regard (Melone & Borgo, 2020) (Amerio et al., 2020) (Alraouf, 2021). Concurrently, in this perspective, the advanced technologies - such as eXtended Reality (XR)- are increasingly used to early acknowledge people responses in terms of spaces' satisfaction. However, in this regard, is it possible to take a step back and understand the impact that such immersive technologies have on users' conscious and unconscious responses? We're witnessing an increasing digitization both in our daily lives and in the working environment to such an extent that the virtualisation of the spaces -for knowing the customer satisfaction in advance as well as for creating an alternative world- is becoming an increasingly debated issue. For this reason, it becomes critical and extremely relevant to understand what impacts immersive spaces have on people's well-being. Although the importance of user experience in terms of well-being has been traditionally recognised, few studies have been conducted in the evaluation through scientific wellbeing detection in virtual spaces. Furthermore, despite the medical concurrent and ongoing findings for stress investigation, the implications of these results appear to struggle to be applied in digital design and in design in general. In this sense, medicine is today perfecting an ongoing and relevant theme of stress detection analysis since increasingly stress is becoming a serious problem for users' productivity and efficiency in modern society (Feng et al., 2021) (Attallah, 2020). Although stress is one of the major contemporary problems, it is difficult for people to perceive even if they are subject to high stress levels or not (Sağbaş et al., 2020) and for this reason the research field is working on a method that is able to return real-time stress detection. The role of neurodesign should be able to spotlight and investigate not only the effects of environmental factors on people's behaviour but also study user's biometric parameters, to inform contemporary digital design. However, even if today there is an increasing and updated interest on the influence of the digital design on public health, there is at the same time a significant lack of research (Burton et al., 2011). The research methodology has been conducted through a systematic state of the art tools for well-being and stress detection in order to define the main technologies to use for future applications within the immersive digital design.
The methodological review begins with an extensive literature search to attain the desired research items, namely the well-being detection techniques and tools and it ends, through its synthesis, with the interpretation of the most relevant articles. To obtain pertinent articles on the topic, "Scopus", "Web of Science" and "Pubmed" were used as the primary scientific search engines. In order to collect the most used techniques for people well-being by overcrossing net disciplines boundaries through a interdisciplinary approach, the choice fell to these three databases due to their huge coverage of peer-reviewed journals and conference proceedings in environmental psychology, medicine, construction, architecture and design. The time span for publication was not restricted to

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Eleonora D'Ascenzi, Vito Getuli, Irene Fiesoli, *Application of Smart Technologies for Assessing Users' Well-Being for Immersive Design Strategies: A State-of-the-Art Review,* pp. 91-99, DOI 10.36253/979-12-215-0289-3.09

recent times due to the willingness to maximise the inclusiveness of the searched items and obtain a wider possible framework. The first step of the literature research has been identified with the definition of the research scope and identification of keywords.
After that, a short listing of the most relevant articles on the theme have been pursued by accurately analysing them for the research purposes, in order to identify the most significative and representative studies. To provide a comprehensive review of the existing literature, this research led to an in-depth study and qualitative analysis of the contents, to present the main analysis carried out on the subject theme. As such, after a first reading of the articles, a deepening phase with the gathering of the main used techniques for well-being detection for evaluating immersive experience was collected. Thus, stress detection tools currently used in medicine have been investigated to understand if could be possible to apply these for well-being evaluation in the frame of immersive digital environment.

2. LITERATURE REVIEW FINDINGS

This section aims at providing an in-depth discussion of the important findings of the reviewed literature with the aim to underline the well-being measurement techniques to be exploited in construction.
The organisation of this section is twofold: first, it presents a collection of stress detection parameters; then, it provides insights regarding the tools to detect stress. Despite the extensive acknowledgment of the impact of the built environment on users' well-being and the recent advancement of smart technologies, just a limited attention has been dedicated to digital design studies of the consequences of immersive environments on the health of occupants. Furthermore, to validate virtual spaces, even a more restricted consideration has been dedicated to the application of smart technologies derived from different research areas. Thus, a focus on the implementation of operating procedures for assessing health and well-being were analysed and reported in the present paragraph by especially referring to psychological and medical research sphere that could be employed in construction and occupancy evaluation. However, not all the initially founded methods have been reported due to the inconsistency between the encountered medical techniques and the application in the digital immersive design field. The below-listed stress detection parameters and tools have been investigated due to their possible use for design research purposes.

2.1 Identification of the main stress detection parameters for stress detection to be implemented for evaluating immersive experience

The following sub-paragraph outlines the output of the research investigation through a brief synthesis of the main techniques adopted for stress detection. As follows, 10 kinds of stress detection adopted data have been identified as well as 6 main techniques to collect them. The following list represents the techniques most used in medicine and psychology for which exist technology and techniques that could be used also in immersive environments for planning process, management and control of virtual reality setting, as well as the detection of quality experience (Fig.1)

(1) Electrodermal activity (EDA)

Electrodermal activity (EDA) also known as Galvanic Skin Response (GSR) or Skin Conductance (SC) is an objective tool of stress indication. EDA measures the changes in conductance at the skin surface due to sweat production that is representative of the intensity of our emotional arousal. It could be considered as a non-intrusive control tool, and for this reason it has been used in many studies thanks to the use of wearable devices (Acerbi et al., 2017; Anusha et al., 2020; Debard et al., 2020; Delmastro et al., 2020; Kalimeri & Saitis, 2016; Minguillon et al., 2018; Mozos et al., 2017) or embedded sensors (Affanni et al., 2018; Sriramprakash et al., 2017a; Zalabarria et al., 2017) able to detect it.

(2) Heart Rate Variability (HRV)

While Heart Rate is the average number of beats in a minute, Heart Rate Variability (HRV) is defined as the standard variation of inter-beat intervals (Elzeiny & Qaraqe, 2018). HRV could be considered a biometric parameter upon which to determine people's stress conditions. Thanks to the use of a tool able to detect heart signals, HRV could be easily collected through wearable devices (Acerbi et al., 2017; Debard et al., 2020; Rani et al., 2002) or other monitoring tools with specific sensors (Mozos et al., 2017; Reanaree et al., 2016; Sriramprakash et al., 2017b; Zalabarria et al., 2017)(Mozos et al., 2017) or a traditional ECG. HRV could be also combined with social media microblogs (Feng et al., 2021).

(3) Electroencephalogram (EEG)

Electroencephalogram (EEG) is a tool to detect real-time stress in daily life by means of the use of specific headsets and its signals. Many studies analyse stress levels thanks to the use of brain electrodes in this technique (Attallah, 2020; Elzeiny & Qaraqe, 2018; Kalas & Momin, 2016; Reanaree et al., 2016) and helmet(Kalimeri & Saitis, 2016). Although from a medical point of view it could be a non-invasive method thanks to the use of scalp surface, from a perspective of stress monitoring, on the contrary, it is quite intrusive since it requires the use of electrodes.

(4) Electromyogram (EMG)

Electromyography (EMG) could be considered as another stress alarm system. EMG measures muscle response for evaluating electrical activity. It is not easy to apply this method for stress detection in a built environment. Several studies use this method for real-time detection of stress levels (Elzeiny & Qaraqe, 2018; Ghaderi et al., 2015; Minguillon et al., 2018).

(5) Cortisol

Cortisol is a hormone made by the adrenal glands that control mood and fear, and it is one of the most used biomarkers for stress levels. Salivary cortisol increases the brain's use of glucose and is one of the most indicative factors which can analyse stress level. It could be measured by means of pipettors although it is not the most suitable for the built environment even if it is one of the most used in medicine as demonstrated through the huge usage (Pascoe et al., 2017; Qiao et al., 2017; Wells et al., 2014).

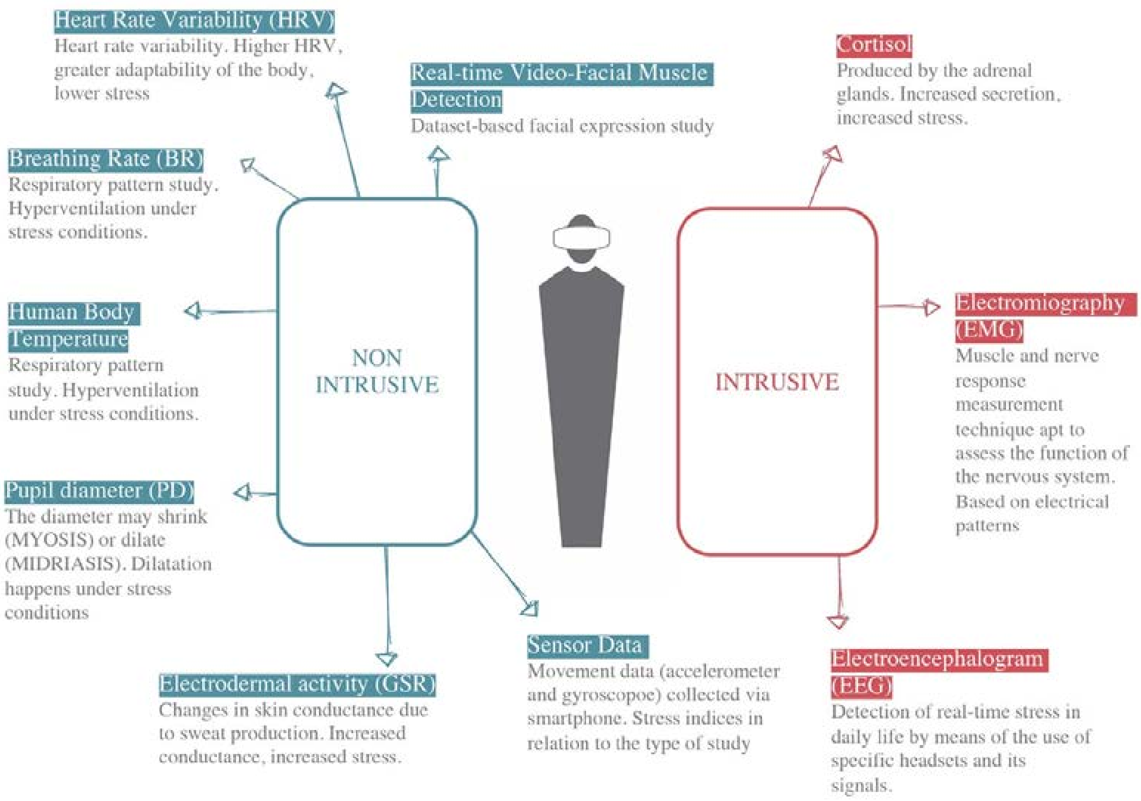

Fig. 1: Non-intrusive and intrusive parameters for evaluating immersive experience

(6) Human Body Temperature

The temperature of the human body could be one of the main data factors upon which it is possible to study stress. According to Rachakonda et al. (2019), in fact variation in body temperature is indicative of the physical and mental condition of people within a specific value range to identify high, medium and low stress. Many studies detect stress through this method by means of contact sensors ((Bin et al., 2015; Rachakonda et al., 2019) or non-contact sensors ((Elzeiny & Qaraqe, 2018).

(7) Pupil Diameter

Pupillometry is a primary index to investigate psychological phenomena. The diameter of the pupil reflects the correlation between its dimension and a human's well-being. The pupil can expand (this phenomenon is called mydriasis) or shrink (in this case it is defined as miosis). When the human body is under stress it induces mydriasis and hence pupil dilatation that can be measured through accurate tools that have also been used in the analysis of stress detection (Al Abdi et al., 2018; Gunawardhane et al., 2013).

(8) Breathing Rate

Another stress biomarker response is given by Breathing Rate. The respiratory pattern can be altered by stress and it can easily be measured with wearable devices(Can et al., 2019; Mozos et al., 2017) or specific tools (Al Abdi et al., 2018). If hyperventilation occurs (around 25/40 breathes per minute) the subject can be considered to be under stress.

(9) Sensor data (accelerometer and gyroscope)

Another index of stress can be indicated through data obtained by accelerometers and gyroscopes. The accelerometer sensor gives real-time information about motion and the related stress interpretation of data as shown in some research projects (Debard et al., 2020; Sağbaş et al., 2020).

(10) Real-time Video-Facial Muscle Detection

Video-Facial Muscle Detection demonstrates how a bespoke machine learning support vector machine (SVM) can be utilized to provide quick and reliable classification. Facial Muscle Detection Algorithm, machine learning and deep learning are today increasingly used for detecting stress (Healy et al., 2018; Zhang et al., 2020a).

(11) Others

Moreover, other studies focus on hand movements (Reanaree et al., 2016), tweeting content (Zhao et al., 2016) keyboard typing (Sağbaş et al., 2020; Vizer et al., 2009) and audio detection (Abburi et al., 2016).

2.2 Identification of the main adopted techniques for stress detection to be implemented for evaluating immersive experience

In this section the main techniques used for collecting stress detection's parameters have been outlined and synthesised as schematically reported. As mentioned in the previous paragraph, several parameters could be analysed for stress detection purposes and along this line, the main adopted techniques to detect (sometimes even simultaneously) well-being variables have been analysed (Fig.2).
Among others, it is worth mentioning:

(1) Wearable devices

Wearable devices are the tools most used to detect stress due to their versatility as well as their non-intrusiveness. Moreover, these kinds of instruments are accessible to all and for this reason they can be easily chosen for daily stress detection studies (Anusha et al., 2020; Debard et al., 2020; Delmastro et al., 2020; Mozos et al., 2017). In regard to physiological data collected, the majority presented on the market are able to detect HRV, EDA, BR, hand movement. Moreover, some smart wearable systems can collect ECG measurement such as Biopacs MP150, MP35 and Shimmer Sensing 3 (Can et al., 2019). Due to their non-invasiveness, they are sometimes employed without the user being aware of it.

(2) Smartphones

Among the unobtrusive devices for ten collections of physiological data, the common smartphone should be mentioned. Multiple features can be extracted from smartphones such as: accelerometer, audio classification, the time and duration of calls, light sensor data, gps information, screen mode changing frequency, videos, wi-fi conversations and so on (Gjoreski et al., 2015). The correlation between stress and collected smartphone data produces significant results. However, according to Can et al. (2019) the low classification of accuracy highlighted by Gjoreski, suggested the importance of adopting an integrated method with the support of the use of wearables and to not rely just on smartphones.

(3) Machine learning

Wearable devices as well as smartphones generate a massive amount of data to be processed, which sometimes necessarily requests the support of machine learning techniques, a branch of artificial intelligence. The issues of the big data generated, as well as their continuous flow demand algorithmic calculation for combining usage behaviours and collected data (Delmastro et al., 2020; Sağbaş et al., 2020). To provide a reliable categorisation, bio-parameters such as Breathing Rate, Galvanic Skin Response and Heart Rate are usually collected and analysed by machine learning systems via the main common classifiers such as K-nearest neighbour (KNN) and support vector machine (SVN) (Ghaderi et al., 2015). Moreover, in the scientific literature, new models for machine learning have been created specifically for detecting emotions through human face recognition (Healy et al., 2018).

(4) Neurosky headset
Stress detection can also be analysed through an intrusive wearable device, namely the EEG Neurosky headset which is a tool to monitor and record the electrical activity of the brain via electrodes placed in the headset. According to Reanaree et al. (2016) the Neurosky Headset could also be complemented by an intelligent watch made by Arduino that has been used in his project (Reanaree et al., 2016).

(5) Applied sensors
A number of applied sensors for Galvanic Skin Response (GSK), Electrocardiogram (ECG), Electroencephalogram (ECC) are available on the market. Differently from wearable and smartphones, these applied sensors are invasive, and the user is conscious of being under observation without specifically knowing the reason why. Although these kinds of applied sensors are different from each other, they can collect multiple signals or one single bio-parameter. At the same time, they can be both easily be portable and/or not movable (Attallah, 2020; Kalimeri & Saitis, 2016; Minguillon et al., 2018; Pandey et al., 2016).

(6) Images/video/ audio capturing tools
Other fundamental tools to be considered other than smartphones are video, audio and image-capturing devices. Among them, especially used for reaching out to a large number of people rather than to an individual person, are video cameras and contact-free camera sensors. By guaranteeing a cost-effective system, these are the most frequently used tools to detect users' facial expressions (Abburi et al., 2016; Zhang et al., 2020b).

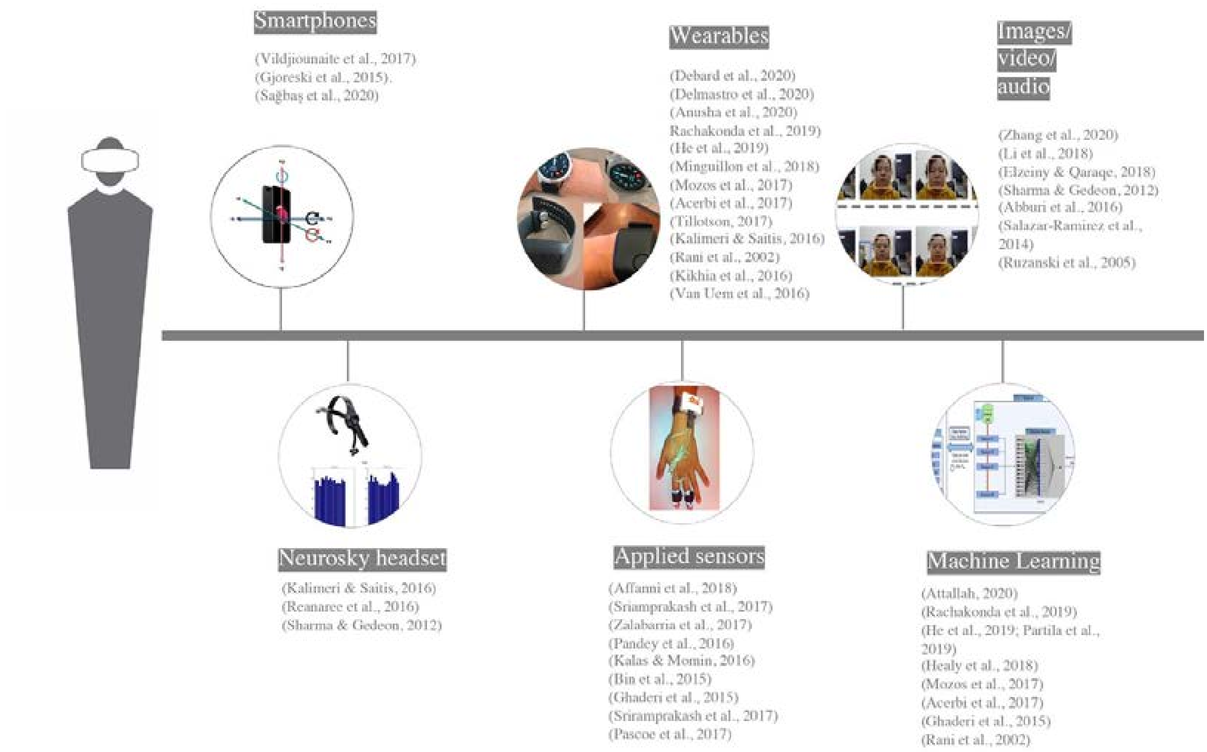

Fig. 2 Non-intrusive and intrusive techniques for evaluating immersive experience

3. DISCUSSION
In order to use them for future applications within the analysis of wellbeing in the digital immersive field, the present review summarizes the main technologies used in medicine. This investigation aims to disseminate tools and methodologies to make designers conscious of the actual impact of the digital environment in daily life and to

encourage planners to better design spaces by bearing in mind the impact of immersive environment on the users' well-being. To address this, a holistic approach is required since the comprehension of the high potential of a interdisciplinary concept that moves from the medical field to design is crucial. Based on the lessons learned from the COVID-19 pandemic, the role of this integrated approach is to provide an informational method that could reduce the gap between architects, engineers, and designers in regard to the expressed or unexpressed responses of users in terms of digital impact of immersive environments. As such, this review investigates the stress bio-parameters to be adopted in immersive digital design to outline possible indicators of high-quality satisfaction for new digital environments, by using not only qualitative data such as interviews and self-reported evaluation, but also quantitative data given by body feedbacks that inform through their unconscious responses. In this paper, the authors have reported two macro areas, namely stress bio-parameters and the related tools, to be applied in design as possible well-being indicators. The most recurring stress parameters as well as the main tools embraced in other fields, have been reported to give a complete overview of the current usage from which digital immersive design could extrapolate the non-invasive techniques with which to ascertain the impact of design strategies on the user's satisfaction. Our body is affected by the choice and design strategies adopted by virtual reality architect, engineers, and designers. There must be a scientifically recognised method to evaluate their implications for users' well-being that goes beyond the traditional qualitative data susceptible to respondents' bias. Choosing the most appropriate tool depends on the availability of resources, targets, and specific research purposes. Some advanced techniques such as video and picture analysis through machine learning, if properly used, could be beneficial for reaching out to the well-being analysis of a mass numbers of users. Therefore, the measurement of eye-pupil diameter and facial muscle movements are required for this type of analysis. It is different in the case of the analysis of a small number of users where artificial intelligence is not required. In this case, the analysis of Heart Rate Variability, Electrodermal Activity and Breathing Rate could be considered as the most informative techniques since, even an ordinary wearable can easily acquaint stress levels. However, adopting a transdisciplinary approach in which these technologies could be supplied to more deeply, investigation of the relationship between users and the built environment is advisable. Although it is widely recognized that human beings respond cognitively, emotionally and physiologically to the built environment, on the other hand, interdisciplinary studies of the physiological well-being connected to immersive environments seem to be lacking, underlining a gap that if investigated could be promising for construction. In this regard, an arising field called "neuroarchitecture/neuro design" is raising the question of how architecture can benefit from its intersection with neuroscience. However, so far, few scientific practical studies have been pursued. For this reason, this conceptual model based on the adoption of practical methodologies represents a central challenge of the present time and is expected to help the digital design researchers to integrate well-being medical analysis into the design evaluation process. Therefore, the authors attempt to improve this conceptual model in future case studies.

4. CONCLUSION AND FUTURE DEVELOPMENTS

The ongoing debate about the increasing digitisazion has raised people's awareness of the impact of the new immersive technologies. Although there is ample evidence in the scientific literature on how the living and working environment impact the psychophysiological states of the users, and despite a recent and ever-growing awareness, only limited attention has been paid to systematic research to find a quantitative tool for the detection of the effect of the virtual space characteristics on the psycho-physiology and perception of the users. The lack of a quantitative approach to evaluate users' impact should be filled by the ability to adapt medical technologies to compelling digital design requirements. Despite growing interest in research into crossing findings from different investigation fields, the application of medical results in digital environment field seems to be defective as demonstrated in the present literature. However, focusing on the trending results could help to explore promising eXtended Reality areas. Thus, by moving forward to the concept of virtual environment design, the questioning of digital spaces should be fundamental to tackle real human well-being intended as mental and emotional health, especially in these current times where the world "metaverse" is increasing advancing. Until today the use of new technologies has been focused on physical built environment rather than on eXtended Reality spaces.

Advanced research and interventions are necessary to deeply investigate the relationship between users and immersive environments. Currently, as far as we know at the time of writing, the use of bio-parameters in digital design is limited to few experimental trials mainly related to marketing field and not yet validated and introduced in the design practice as a validation method for immersive quality analysis. Therefore, if these technologies could be implemented and correctly integrated in digital design, the role of neuro-design would be enhanced. Medicine has a huge potential to inform design, and the impact of medical findings could be applied in digital design. A holistic and interdisciplinary approach could be largely adopted by opening the door to the fruitful pollination of different research fields with a clear goal: to design high quality digital environment place for wellbeing and the high-quality experience of the users. Following this, the authors have identified the applications within eXtended

Reality where the well-being analysis by using stress detection can make the best impact: real-time responsive design based on a human-centric approach; users' well-being monitoring in immersive environments; eXtended Reality "certification" based on human perception; education tools for designers and users to sensitize them to the impact of digital design on users' wellbeing; critical evaluation of extended reality design; real-time interpretation systems which arrange immersive experience variables such as illumination, length of experience, quality of design and so on. This conceptual framework aims to help, during the design process to ensure the proper attention to users' well-being. In short, there is a long road to travel, and much work needs to be done. This review is expected to help designers to rethink the impact of the digital environment in the light of the tangibility of objective and measurable data based on the well-being of users. The COVID-19 pandemic forces us to be aware of digital design implications. For an optimal design experience, our article directs a spotlight on the need for the adoption of medical techniques to evaluate the physical and mental users' well-being of the growing and ever evolving use of eXtended Reality.

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INVESTIGATING THE ABILITY OF IMMERSIVE VIRTUAL ENVIRONMENTS TO FACILITATE OCCUPANT THERMAL STATE DATA COLLECTION INVOLVING FACE MASKS

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ABSTRACT: *This study examines the capability of an immersive virtual environment (IVE–based) experimental protocol to support occupant thermal state (sensation, acceptability, and comfort) data collection when participants wear face masks. Specifically, the goal is to see if there is a change in local thermal states due to face covering and would such a change affect overall thermal states. A between-subject experiment was conducted with fifty-four participants (27 masked; 27 unmasked) who were exposed to three-step temperatures (18.3ºC, 23.8ºC, and 29.4ºC) in a climate chamber under both cooling and heating sequences. In masked IVE experiments, participants donned a face mask and viewed the chamber's virtual model on a head-mounted display. In contrast, in unmasked IVE experiments, participants didn't use a face mask. Skin temperatures and overall/local thermal state responses were collected during the experiments. They were then statistically compared between masked IVE and unmasked IVE experiments. The results suggest that forehead temperature was significantly different under all step temperatures in the cooling sequence, with mean forehead temperature being larger in masked IVE than in unmasked IVE experiments. Furthermore, in masked IVE experiments, thermal sensation in the forehead, neck, and upper-back increased while the thermal acceptability in those same skin sites decreased, but this difference was not statistically significant. Also, in masked IVE experiments, the overall thermal sensation increased, whereas both the overall thermal acceptability and comfort decreased when compared with unmasked IVE experiments. Nonetheless, this difference was not statistically significant. To summarize, wearing a face mask didn't affect the participant's overall and local thermal states in IVEs, although few statistical differences were observed in skin temperatures.*

KEYWORDS: *Immersive virtual environment, thermal sensation, thermal comfort, thermal acceptability, face masks.*

1. INTRODUCTION

Immersive virtual environments (IVEs) are a technology that combines software and hardware systems to produce a virtual or simulated environment that arranges sensory input in a way that makes the user feel as though they are inside the virtual environment. With the help of this sensory input, the user becomes cognitively engaged and interacts with the elements of the virtual environment (Radianti et al., 2020). Head-mounted displays (HMD) are the most popular method to deliver IVEs because they are easy to set up and provide a wide field of stereoscopic vision. In a true 1:1 scaled setting, IVEs generally provide a favorable environment for sophisticated data collection methods, allowing researchers to effectively modify desired variables and test hypotheses at lower costs and shorter experimental times (Alamirah et al., 2022). As a result, IVEs are more frequently employed to research how occupant perception and satisfaction with the tested conditions are affected by changes in ambient conditions (such as lighting settings) (Heydarian et al., 2016). Specifically, IVEs are used to study the occupant's thermal states (thermal sensation, acceptability, and comfort) by incorporating thermal conditions through the use of closed environments like climate chambers (Rentala et al., 2021). Studies have also examined how well IVEs can simulate actual physical settings when evaluating users' comfort (Yeom et al., 2019). Other researchers used IVE to look at how people's perceptions of their indoor environment are influenced by psychological, physiological, and environmental factors (Chinazzo et al., 2020).

The general IVE experimental protocol for studying occupant thermal states usually consists of subjecting the participants to a building design in IVE while simultaneously manipulating environmental conditions such as operative temperatures, humidity, etc., in a test environment (e.g., climate chamber) and collecting their physiological (e.g., skin temperature, heart rate, etc.) and thermal perception responses (e.g., thermal sensation, acceptability, and comfort) (Alamirah et al., 2022). Normally, during these experiments, the participants do not wear any face coverings or face masks. However, there are certain situations where the IVE experiments must be performed with the participants wearing a face covering or a mask for health and safety purposes, such as during the COVID-19 pandemic. This mask-wearing presents new challenges for occupant thermal state experiments using IVEs. Face mask usage affects the respiratory system. It specifically interferes with breathing normally,

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Girish Srivatsa Rentala, Yimin Zhu, *Investigating the Ability of Immersive Virtual Environments to Facilitate Occupant Thermal State Data Collection Involving Face Masks,* pp. 100-108, DOI 10.36253/979-12-215-0289-3.10

causing some carbon dioxide to be expelled and some inhaled throughout each breathing cycle (Lazzarino et al., 2020). Moreover, wearing a mask will directly lower the amount of oxygen inhaled by the body and prevent heat transmission between the facial region and the environment (Hu et al., 2022). Also, when wearing an HMD, the participant's face is already covered, which can trap heat and cause discomfort (Mehrfard et al., 2019). Adding a face mask on top of this can exacerbate the heat buildup, affecting a person's overall thermal state. As a result, it is reasonable to assume that using a face mask during IVE experiments may significantly impact how participants' thermal sensation, acceptability, and comfort are evaluated, thereby impacting the validity of IVE experiments. Therefore, it is necessary to investigate the effect of using face masks on participants' thermal states in IVE experiments. In this study, human subject experiments were performed in IVE under three-step temperatures in a climate chamber with participants who wore face masks (referred to as masked IVE experiments) and participants who did not wear face masks (referred as unmasked IVE experiments). Local skin temperatures and both the overall and local thermal state responses were collected. We hypothesize that the local skin temperatures, local thermal states and overall thermal states between the masked IVE and unmasked IVE experiments will differ significantly. The results of this analysis would provide new insights into developing IVE experimental protocols for occupant thermal state research particularly regarding the mask use. That is, whether to modify the experimental protocol to account for mask wearing or continue using the existing one when face masks needed to be used during the experiments.

2. METHODOLOGY

2.1 Participants

This study was approved by the university's Institutional Review Board. A total of fifty-four participants were enlisted for this study. Half of the participants did the masked IVE experiments, and the other half did the unmasked IVE experiments. Participants in both experimental groups are divided roughly equally by gender and age, with 15 men and 12 women participating in masked IVE experiments with a mean age of 21.9 years and 14 men and 13 women participating in unmasked IVE experiments with a mean age of 22.3 years, respectively. This was done to ensure that gender and age would not affect the results when statistically comparing the two groups.

2.2 Immersive Virtual Environment

Both masked and unmasked IVE experiments were carried out inside a climate chamber that was located on the university's campus. An immersive virtual environment of the climate chamber was delivered via an HTC Vive head-mounted display device. The chamber's 3D model was produced with Autodesk 3ds Max. The model, together with the material textures and lightmaps, was loaded into Unreal Engine 4, as shown in Figure 1. The climate chamber offers space heating and cooling in an IVE experiment for measuring occupant thermal states. At the same time, the users observe the virtual world of the chamber interior via a head-mounted display (HMD).

Fig. 1: Climate chamber's virtual environment

2.3 Experiment Procedure

Between-subject experiments were conducted using the procedure outlined in Figure 2. After the participants signed the consent forms, they were given a demographics survey and were asked to arrive at the chamber in a specific set of clothing (clo of 0.5-0.6), which included trousers and a T-shirt or a long-sleeve shirt. After coming to the chamber, the participants were tested for cigarette or alcohol use using the pre-experiment screening survey in the chamber's resting area, where the temperature and relative humidity were set to 75ºF/23.8ºC and 50% RH, respectively. Participants were excluded from the study if they were found to have used cigarettes or alcohol. The screening took about 10 minutes to complete and allowed the participants to adjust to the chamber's temperature and lessen the impact of their previous thermal state. Then, the participants were asked to enter the chamber's testing area and have the skin temperature sensors (Vernier surface temperature sensors; accuracy: ± 0.5 °C, resolution: 0.1 °C) attached to their bodies at eight locations, i.e., forehead, neck, chest, upper back, forearm, hand, calf and foot.

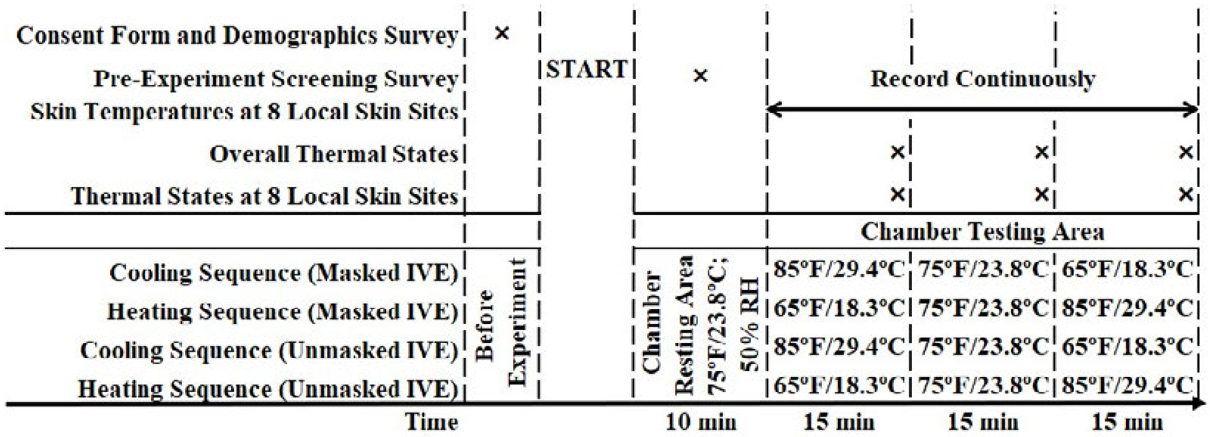

Fig. 2: Experiment procedure

Twenty-seven participants participated in masked IVE experiments, and another twenty-seven participants participated in unmasked IVE experiments. In masked IVE experiments, the participants wore a face mask that entirely covered the mouth and nose area and viewed the chamber's virtual model through the HTC Vive device, as shown in Fig. 3 (left). Whereas in unmasked IVE experiments, the participants only viewed the chamber's virtual model without wearing a face mask (Fig. 3 (right)). Also, both masked and unmasked IVE experiments consisted of cooling and heating sequences that were conducted at least two weeks apart. The cooling sequence had a decrease of three-step temperatures, i.e., 85ºF/29.4ºC –> 75ºF/23.8ºC –> 65ºF/18.3ºC and heating sequence had an increase of three-step temperatures, i.e., 65ºF/18.3ºC –> 75ºF/23.8ºC –> 85ºF/29.4ºC. So, overall there were four experimental sessions, i.e., (1) masked IVE in the cooling sequence, (2) masked IVE in the heating sequence, (3) unmasked IVE in the cooling sequence, (4) unmasked IVE in the heating sequence. The order of the four experimental sessions was random to reduce the order effect and was conducted with a set humidity of 55% RH and a CO_2 limit of 1,000 ppm. From the start of each trial until the end, the indoor control temperature around the participants (sensor placed at the height of 24 inches from the floor (ASHRAE, 2013)) and their skin temperatures were continuously recorded at one-second intervals. Following the stabilization of the indoor control temperature at each step temperature, the participants were subjected to that stabilized temperature for about 5 minutes, and then their overall and local thermal state votes were recorded. The thermal states included responses for thermal sensation, thermal acceptability, and thermal comfort. For local thermal states, only thermal sensation and thermal acceptability were recorded at the exact eight locations where the skin temperatures were sampled from. The ASHRAE Standard 55 Thermal Comfort seven-point scale was used to record overall and local thermal sensation (ASHRAE, 2013). In contrast, six-point scales were used to record the overall thermal comfort and overall/local thermal acceptability (Rentala et al., 2021).

Fig. 3: An experimental session with mask (left) vs. without mask (right).

2.4 Data Processing

After completing the experiments, the mean of the skin temperatures at eight sites and the indoor control temperature for each participant was calculated using the last five-minute data (i.e., data from when the control temperature stabilized to the end of the end thermal state surveys). This 5-minute averaged data was used for all statistical analyses. Furthermore, the mean indoor control temperature was statistically compared between masked IVE and unmasked IVE experiments under all step temperatures in both cooling and heating sequences to ensure that the indoor temperature was properly controlled and remained the same in both sets of experiments. A two-tailed independent sample T-test was used for comparisons. The tests revealed that the p-values in all the cases were not statistically significant ($p > 0.05$), indicating that the control temperature in the masked IVE experiments was comparable with unmasked IVE experiments.

3. RESULTS

Several statistical tests were performed to test the hypothesis that the local skin temperatures, local thermal states, and overall thermal states were significantly different between masked IVE and unmasked IVE experiments under all the step temperatures in both cooling and heating sequences. Independent sample T-tests were used to compare the skin temperatures collected at eight local sites. Wilcoxon Rank Sum tests were used to compare the local and overall thermal state responses. All statistical tests were performed at the significance threshold of 0.05.

3.1 Skin Temperature

Table 1 shows the results where the mean forehead temperature significantly differed ($p < 0.05$) between masked and unmasked IVE experiments under all step temperatures in the cooling sequence. Also, in the cooling sequence, the forehead temperature was higher in masked IVE than in unmasked IVE by an average of 0.5°C under all step temperatures. However, no significant differences in the forehead temperature were observed in the heating sequence under all the step temperatures, even though the forehead temperature under all step temperatures was higher in masked IVE than in unmasked IVE by an average of 1.06°C in the heating sequence. In addition, no significant differences were observed in skin temperatures at other sites (i.e., neck, chest, upper back, forearm, hand, calf, foot) between masked and unmasked IVE experiments under all step temperatures in both cooling and heating sequences. However, like forehead temperature, the neck, chest, upper back, forearm, hand, calf, and foot temperatures were higher in masked IVE than in unmasked IVE experiments by an average of 0.55°C, 0.57°C, 0.49°C, 0.66°C, 0.52°C, 0.48°C, 0.69°C under all step temperatures in both sequences.

Table 1: Independent sample T-test results of skin temperatures

Experiment sequences	Step Temperature	Skin Sites	Masked IVE		Unmasked IVE		p
			Mean (ºC)	SD	Mean (ºC)	SD	
Cooling	65 ºF/18.3 ºC	Forehead	36.75	0.43	36.13	0.71	0.001
	75 ºF/23.8 ºC	Forehead	36.7	0.45	36.17	0.58	0.001
	85 ºF/29.4 ºC	Forehead	36.49	0.41	35.99	0.49	0.001

3.2 Overall Thermal States

The mean overall thermal sensation votes were higher in masked IVE experiments than in unmasked IVE experiments by 0.44, 0.36, 0.4, 0.46, 0.27, and 0.38 (with an average of 0.38) in all step temperatures under both cooling and heating sequences (Fig. 4). This indicates that wearing a mask increases the overall sensation. Still, this increase was not statistically significant ($p > 0.05$) in all conditions. This result is corroborated by an earlier study in a climate chamber that did not use IVE (Yoshihara et al., 2021). On the other hand, in masked IVE experiments compared to unmasked IVE experiments, the mean overall thermal acceptability votes were lower by 0.28, 0.96, 0.72, 0.26, 0.58, and 0.04 (with an average of 0.47) across all step temperatures during both cooling and heating sequences (Fig. 5). Similarly, the mean overall thermal comfort votes were lower by 0.08, 1, 0.44, 0, 0.75, and 0.87 (with an average of 0.52) in masked IVE experiments when compared with unmasked IVE experiments across all step temperatures during both cooling and heating sequences (Fig. 6). These findings indicate that wearing a mask reduces the overall thermal acceptability and overall thermal comfort. However, similar to the results observed for overall thermal sensation, the decrease in overall thermal acceptability and thermal comfort was not statistically significant in all conditions. These results are consistent with an earlier study conducted in a non-IVE climate chamber (Zhang et al., 2021).

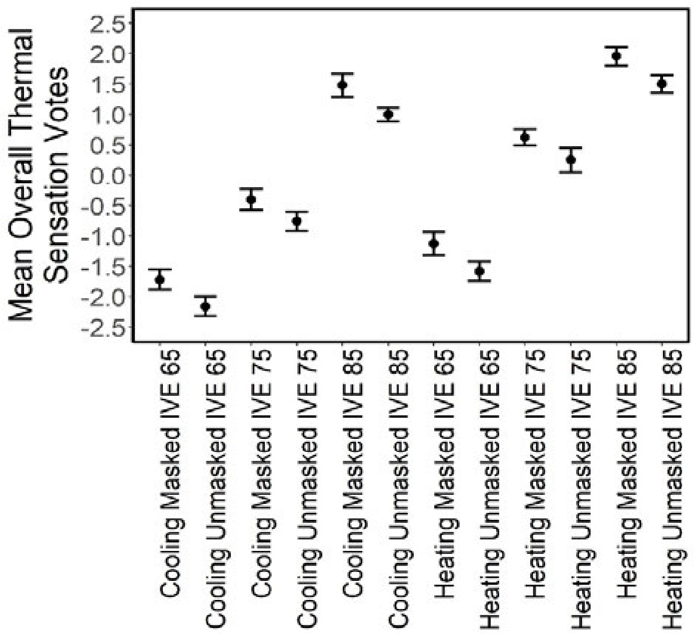

Fig. 4: Mean overall thermal sensation votes.

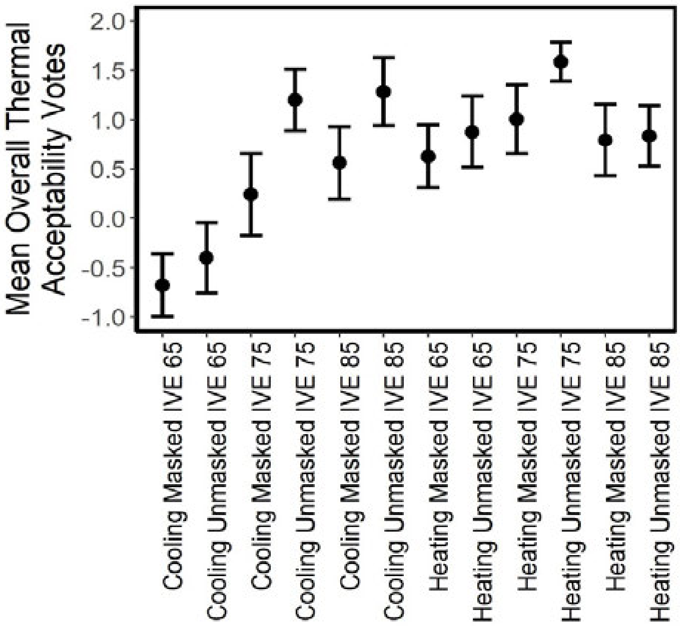

Fig. 5: Mean overall thermal acceptability votes.

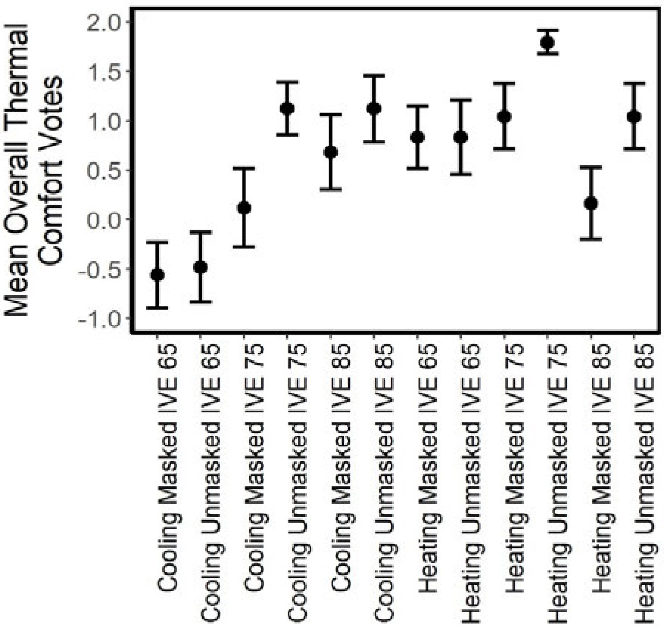

Fig. 6: Mean overall thermal comfort votes.

3.3 Local Thermal States

The thermal sensation and thermal acceptability at the eight local skin sites were also analyzed. The mean thermal sensation on the upper body, specifically at the forehead, neck, and upper back, increased by an average of 0.5, 0.18, and 0.24, respectively, in masked IVE when compared with unmasked IVE under all step temperatures in both cooling and heating sequences (Fig. 7). This finding is partially supported by a prior non-IVE study where they reported higher mean thermal sensations at only forehead and upper back (Tang et al., 2022). Also, the reason for the thermal sensation increase is that mask use can affect the frequency of breathing, leading to heat buildup around the face and neck area, causing the participants to feel warmer (Zhang et al., 2021). On the contrary, the thermal acceptability at those same three skin sites decreased by an average of 0.62, 0.23, and 0.16, respectively, in masked IVE when compared with unmasked IVE, under all step temperatures in both cooling and heating sequences (Fig. 8). However, the increase in thermal sensation and decrease in thermal acceptability at those three skin sites were not statistically significant ($p > 0.05$) in all step temperatures under both cooling and heating sequence even though the forehead temperature was statistically significant in the cooling sequence (Table 1). Similarly, thermal sensation and thermal acceptability at other skin sites (chest, forearm, hand, calf, and foot) were also not statistically significant ($p > 0.05$) between masked IVE and unmasked IVE experiments.

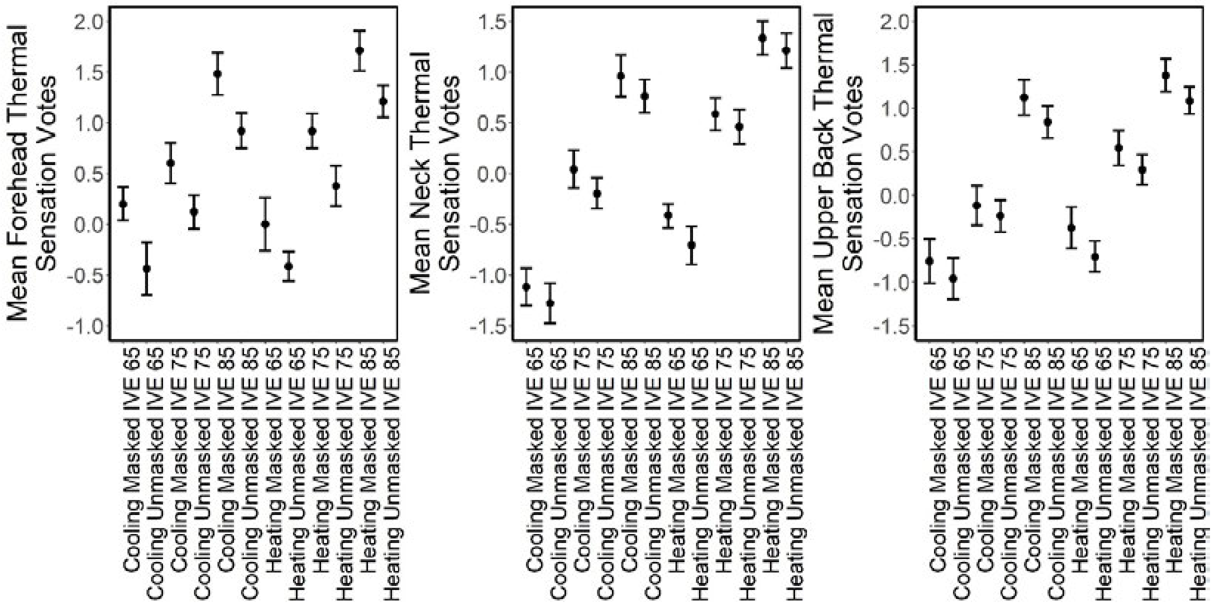

Fig. 7: (Left to right) Mean forehead, neck and upper back thermal sensation votes.

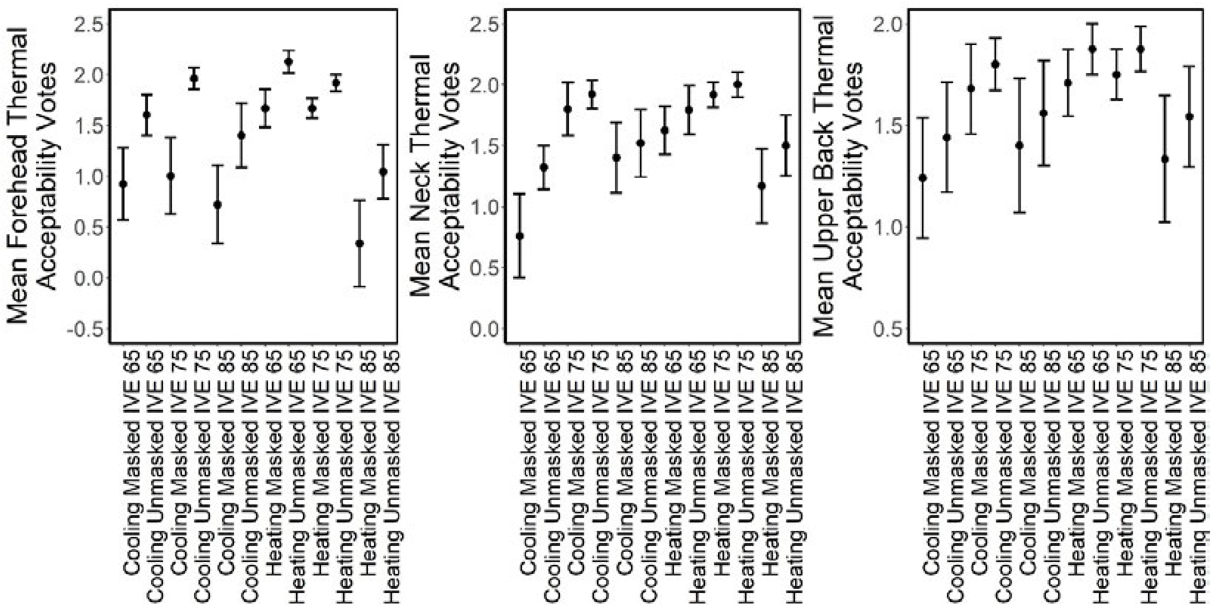

Fig. 8: (Left to right) Mean forehead, neck and upper back thermal acceptability votes.

4. CONCLUSIONS AND FUTURE STUDIES

The study shows that wearing a face covering or mask while performing IVE experiments did not significantly affect the participants' overall thermal states as well as their local thermal sensation and acceptability at the eight skin sites. In other words, an appropriately designed experimental approach can support IVE experiments involving face masks. This approach should include precisely regulating the indoor test environment (e.g., temperature and humidity), offering an adequately designed virtual environment that induces high immersion with minimal motion sickness, and closely monitoring the participants throughout the experiment to make sure the masks are fitted correctly and do not interfere with the experimental apparatus (e.g., sensors). Even though the results were not statistically significant, small differences were observed in the mean votes, such as higher overall thermal sensation and lower overall thermal acceptability and comfort in masked IVE compared to unmasked IVE experiments. Higher thermal sensation and lower thermal acceptability were observed at the forehead, neck, and upper back in masked IVE compared to unmasked IVE experiments. Furthermore, higher temperatures were observed at all eight skin sites in masked IVE than in unmasked IVE under all step temperatures in both sequences. But these results were not statistically significant except at the forehead in the cooling sequence. Also, the increase in forehead temperature did not affect the forehead sensation, acceptability, or overall thermal states. While the results are noteworthy, they may be affected by some limitations. Firstly, the sample size within both the masked and unmasked groups was relatively small (n = 27). Therefore, the lack of statistical significance in the results could be attributed to the small sample size. Future investigations should aim to explore the impact of face masks on the validity of the IVE experimental protocol using a larger sample size. Secondly, this study only accounted for indoor air temperature and skin temperature, and future research may extend its scope to incorporate other environmental and physiological factors, such as the impact of relative humidity, air velocity, skin electrodermal activity, and heart rates. Finally, future studies may test the validity of the IVE experimental protocol involving mask use in different outdoor temperature conditions or seasons.

5. ACKNOWLEDGEMENT

This study was funded by the National Science Foundation under Grant No. 1805914. Any comments, research results, or suggestions made in this article are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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SEAMLESS INDOOR/OUTDOOR MARKER-LESS AUGMENTED REALITY REGISTRATION SUPPORTING FACILITY MANAGEMENT OPERATIONS

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ABSTRACT: *Augmented reality (AR) still struggles to be widely used in real processes in the construction industry despite its great potential. This is partly due to the difficulties that exist in aligning holograms and maintaining their stability, especially for outdoor applications. In addition, being indoor-outdoor interactions crucial for built environment management, it would be important that AR apps can work seamlessly. Alignment in indoor environments cannot make use of methods such as GNSS, nor can all environments be assumed to have been previously initialized with AR tools. Thus, marker-less AR registration is crucial for indoor applications. This paper presents an approach for marker-less AR registration seamlessly in both outdoor and indoor environments. Real-time kinematic positioning (RTK) and Inertial Measurement Units (IMU) technologies have been chosen for outdoor registration, while image comparison based on convolutional neural networks (CNN) for indoor registration. In this research, the application of these two technologies and their integration have been studied and tested on site on a real Facility Management use case related to a university campus. The proposed approach has shown very promising results in displaying BIM elements of the electrical system seamlessly superimposed through AR to their physical counterparts in mixed indoor-outdoor environments.*

KEYWORDS: *Augmented Reality, Seamless Registration, Feature Matching, Pose Estimation, Real-Time Kinematic, Facility Management.*

1. INTRODUCTION

The AECO industry, although commonly recognized as one of the least digitized industries, is increasingly moving towards embracing more and more computer-based technologies to provide better performance in various stages of buildings lifecycle (Albahbah et al., 2021). The Operation and Maintenance (O&M) phase of Facility Management (FM) accounts for the largest proportion of the whole life costs of the building process (Salman & Ahmad, 2023). The costs of the O&M phase represent 50–70% of the total annual facility operating costs and 85% of the entire lifecycle cost of a building. Ever since the facilities started to become more complex, the day-to-day tasks have also become more difficult. In fact, the increased need of the construction industry for visualization technologies arises from the complex nature of the industry and its high demand for information access for assessment, communication, and collaboration. Lack of coordination between facility managers and field workers results in delays and cost overruns which could easily be avoided with better coordination and visualization tools. In this domain, Augmented Reality (AR) technologies can be used as visualization tools for facilities' O&M tasks and can provide significant advantages. AR impacts the mobile computing industry by radically changing the type of interaction between humans and computers. In fact, such technology creates direct, automatic, and practicable connections between the physical world and digital information by providing a simple and immediate user interface to a digitally enhanced physical world. Since AR allows virtual objects to be simultaneously superimposed on the real world, it helps to locate and view the occluded facilities and equipment and provides maintenance guiding instruction for the field workers (Salman & Ahmad, 2023). Through a hand-held device (HHD) or head mount device (HMD), it augments the real world by making implicit information apparent to the user when required. Many journal publications demonstrate that AR technology can be applied to various domains in AECO industry, especially in the O&M phase of the project lifecycle (Baek et al., 2019; Jurado et al., 2021; Naticchia et al., 2021; Vaccarini et al., 2022). For example, current maintenance practices are characterized by scattered and disoriented facility information that the maintenance staff must fetch through specifications, maintenance reports, and checklists. In fact, 50% of the on-site maintenance time is still spent on localizing and navigating targets inside a facility (Salman & Ahmad, 2023). Even after locating the target, maintenance staff must put additional effort into seeing the target as it could be concealed in the case of piping, overhead ducts or behind a wall.

AR poses a number of demanding technological requirements for its implementation (Costanza et al., 2009). One challenge is related to display technology, which has registered remarkable breakthroughs in the last decades. Precise position tracking constitutes another significant challenge. In order to give the illusion that virtual objects

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Leonardo Messi, Francesco Spegni, Massimo Vaccarini, Alessandra Corneli, Leonardo Binni, *Seamless Indoor/Outdoor Marker-Less Augmented Reality Registration Supporting Facility Management Operations,* pp. 109-120, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.11

are located at fixed physical positions or attached to physical items, the system must know the position of relevant physical objects relative to the display system. Since the earliest days, spatial registration has been considered as one of the most important technical aspects of an AR systems and is considered a core part of AR functionality (Albahbah et al., 2021; Salman & Ahmad, 2023). Spatial registration can combine virtual objects and the real environment with the correct spatial perspective relationship by calculating the corresponding relation of both the virtual world and the real-world coordinate systems (Cheng et al., 2020). More in detail, spatial registration is responsible for calculating the user's correct spatial position and orientation in accordance with the real-world coordinate systems (Albahbah et al., 2021).

The spatial registration methods are generally classified into two categories: “marker-based” and “marker-less” methods. The first one is considered the most widely used spatial registration method. Markers can be 2D images with visual features or natural 3D objects in the real environment (Cheng et al., 2020). The high use of this method may be returned to the simplicity, efficiency, and convenience of image recognition for superimposing virtual objects to the real world. Image recognition methods rely on extracting features from images instead of using complicated algorithms for calculating the relationship of relative positions. A similar approach can be applied with invisible markers, such as infrared and RFID ones (El Barhoumi et al., 2022). With marker-less approaches, instead of tracking features of markers, localization technologies are used to control the relative position between the real environment and virtual objects. GNSS is the most popular marker-less localization technology due to its suitability for use in a large open area such as a construction site and the ease of its signal receiving by common mobile devices (Cheng et al., 2020). According to the official US Government information on GNSS, the user range error (URE) for civil commitments cannot reach lower than 0.8 m (Cheng et al., 2020). The localization accuracy of GNSS is much worse in indoor environments, given that the buildings block the GNSS signal. The low accuracy of GNSS is not suitable for activities that require high accuracy or that mainly occur indoors. Compared with GNSS, some other marker-less localization technologies, such as Wi-Fi, Ultra-wideband (UWB), Inertial Measurement Unit (IMU), and Simultaneous Localization and Mapping (SLAM) can provide higher accuracy and can be applied to indoor activities. Another marker-less category is represented by vision-based methods using natural features for registration purposes (El Barhoumi et al., 2022). Each of these methods for spatial registration has its limitations in either accuracy or practicality. To promote the application of AR in the FM, which typically involves both indoor and outdoor environments, an advanced localization method that can provide an accurate and seamless registration in heterogeneous scenarios is needed. In order to cover this gap, a marker-less localization system for seamless indoor/outdoor AR registration has been developed by defining a cloud platform that hosts an indoor registration engine, an outdoor registration engine, plus a switch engine that manages the priority between the two. The developed system, tested on site on a real FM use case related to a university campus, has shown very promising results. The remainder of this paper is structured as follows. In Section 2, a literature review is presented. Section 3 reports the methodology adopted for the development of the proposed system. In Section 4, experiments design and execution on a FM use case are presented. Finally, Section 5 is devoted to results discussion and conclusions.

2. LITERATURE REVIEW

In this section, a literature review concerning existing AR registration methodologies applied to both indoor (Section 2.1) and outdoor (Section 2.2) environments is reported. Understanding strength and eventual gaps of approaches proposed by past studies and commercially available solutions paved the way to the definition of the indoor/outdoor seamless registration system proposed by this study.

2.1 Indoor AR registration

In the AECO industry, several AR registration methodologies for indoor applications have been developed and tested so far. Past studies have exhaustively tested marker-based approaches using visual markers distinctive in the scene (Lee & Akin, 2011; Park et al., 2013). Even though artificial markers are advantageous in terms of robustness in detection, they should be installed all over the facility before on-site activities, such as the actual FM, occur. In addition, visual markers can trigger aesthetic issues because of their distinctive appearance. Alternative solutions are represented by invisible markers, such as infrared (Kuo et al., 2013) and RFID (Carbonari et al., 2022; Naticchia et al., 2021), and natural markers (Koch et al., 2014) that do not aesthetically change the scene. However, even though invisible markers do not have aesthetic issues, they should be pre-installed. Natural markers, instead, have the limitation of depending on signs, including exit signs, fire extinguisher signs, and textual information signs. If the scene does not have such designated signs, the localization can be restricted (Baek et al., 2019). Commercial AR libraries, such as Vuforia (PTC Products, 2023), ARcore (Google LLC, 2023), and World Locking

Tools (WLTs) (Microsoft, 2023) have been tested in indoor environments (Ashour et al., 2022; El Barhoumi et al., 2022). Comparative tests in indoor environments of Vuforia Image Target and WLTs showed better results of the second ones (Teruggi & Fassi, 2022).

Among marker-less methods, GNSS-based AR systems have been largely studied (Kim et al., 2013). However, they are considered inappropriate for indoor applications because of their low accuracy (Chen et al., 2019). Therefore, many studies have employed the Wi-Fi fingerprinting technology for indoor localization purposes (Ahmad et al., 2020; Chen et al., 2019). This approach loses accuracy in the case of multiple mobile devices. In fact, the localization accuracy of the order of 1 m, ensured by Wi-Fi-based collaborative systems (Chen et al., 2019), can be still improved. Another marker-less methodology for indoor localization is based on image comparison. Image-based localization is classically tackled by estimating a camera pose from correspondences established between sparse local features (Ethan Rublee et al., 2011) and a 3D Structure-from-Motion (SfM) (Schönberger & Frahm, 2016) map of the scene (Li et al., 2012). Image comparison methodologies are classified into direct-matching and image-retrieval methodologies (Baek et al., 2019). Direct-matching methodologies do not render images for dataset, but directly find correspondences between 3D structure and the queried image (Humenberger et al., 2020). This pipeline scales to large scenes using image retrieval (Cao et al., 2020). Image-retrieval methodologies attempt to find the closest image to the queried image among the preliminarily prepared dataset. The dataset images can be preliminarily collected by photographs or rendered from three-dimensional structure estimation. Recently, many of these steps or even the end-to-end pipeline have been successfully learned with neural networks (DeTone et al., 2017; Lindenberger et al., 2023; Sarlin, Cadena, et al., 2018). This approach, although may lose accuracy whenever there is lack of context or repetitive elements, has shown great potential to develop indoor AR registration apps with applicability for non-expert users (Baek et al., 2019).

2.2 Outdoor AR registration

AR registration in outdoor environments presents distinct challenges compared to those encountered in indoor environments. Tracking and alignment approaches such as SLAM enable the placement of virtual objects relative to a local reference frame. However, the reliability of such tracking approaches in open environments is compromised due to (i) expanded spatial dimensions, (ii) the absence of readily available reference points, (iii) computational costs in large environments, and (iv) the dynamic nature of external spaces that undergoes frequent changes. Therefore, the AR registration approach in outdoor environments cannot solely rely on local reference systems but must necessarily be based on an absolute reference system, enabling the determination of the geographic pose of both the user and virtual objects (Cyrus et al., 2019; Ling et al., 2019; Marchand et al., 2016). To this end, hybrid AR registration approaches, based on the combined use of IMU and high-precision Global Navigation Satellite System (GNSS) such as the Real-Time Kinematics (RTK), have been pursued for the visualization of underground pipelines and subsurface data (Hansen et al., 2021; He et al., 2006; Roberts et al., 2002), for urban navigation (Guarese & Maciel, 2019; Zhao et al., 2016), for agricultural vehicle navigation (Kaizu & Choi, 2012), and for the alignment of multiple smaller maps from an existing SLAM tracking system (Ling et al., 2019). Even from a commercial standpoint, there are currently not many solutions available that ensure the use of AR apps in outdoor environments either without relying on some kind of additional infrastructures (e.g., markers, QRcode, RFID, beacons, etc.) or without the need of manual/semi-manual alignment procedures, with some exceptions. For instance, Trimble Site Vision (Trimble Inc., 2023) makes use of the built-in GNSS receiver to achieve 1 centimeter of horizontal accuracy under RTK coverage. Similarly, Engineering-grade AR for AEC (vGIS Inc., 2023) developed by vGIS achieves the same centimeter-level accuracy under RTK coverage. In this case the RTK antenna is not directly integrated into the system but needs to be obtained from third-party vendors. However, relying on GNSS technology only means that the system cannot cope with urban-canyon scenarios and indoor environment. Due to these limitations and the persistently high costs, these solutions have not yet experienced widespread adoption in the construction industry. Delving deeper into this last notion, it is noteworthy that the individual components of RTK receivers are economically affordable, thereby fostering the proliferation of applications of this technology (Hansen et al., 2021).

2.3 Research questions

As demonstrated by the literature review reported in Sections 2.1 and 2.2, several AR registration methodologies exist. Limitations of existing indoor AR registration approaches must be considered. Marker-based approaches share the limitation of requiring a preliminary survey to install markers or the existence of signs to be used as natural markers (Baek et al., 2019). Among marker-less approaches, GNSS-based solutions are inappropriate for indoor applications because of the weakness of GNSS signals (Chen et al., 2019), whereas Wi-Fi-based approaches lose localization accuracy in case of multiple mobile devices (Salman & Ahmad, 2023). On the other hand, image-based systems, although may lose accuracy whenever there is lack of context or repetitive elements, show great potential to develop indoor AR registration applications with applicability for non-expert users (Baek et al., 2019). With reference to outdoor AR registration approaches, limitations of marker-less GNSS-based approaches must be considered. First of all, the reduced reliability of GNSS in urban-canyon scenarios (e.g., proximity to urban elements, such as buildings, roofs, trees, and so on) limits possibilities of applications (Cheng et al., 2020; Ling et al., 2019). In addition, GNSS-based solutions are currently expensive (especially for high-precision RTK GNSS systems). Despite this, since single RTK receivers' components are becoming available at affordable prices, the development of in-house devices is showing promising growth (Hansen et al., 2021). Finally, outdoor AR registration approaches are affected by the lack of integration to indoor scenarios, except through the use of additional supporting infrastructure (such as beacons) that constrain the deployment area (Cheng et al., 2020). Considering that indoor-outdoor interactions are crucial for managing the built environment, it would be important that AR applications can work seamlessly even during changes in environment. In addition, in order to ensure a wider applicability of AR, preliminary set up procedures for registration should be as simple as possible. In order to cover these gaps, this study aims to answer the following research questions:

RQ1 What system architecture would ensure a seamless AR indoor/outdoor registration?
RQ2 What technical solutions would make AR registration "plug-and-play" for wider applicability even among non-expert users?

3. METHODOLOGY

3.1 System architecture

In order to answer the research questions (Section 2.3), the system architecture, reported in Fig. 1, has been defined. The proposed architecture is built on top of a BIM Cloud Platform which hosts the following four elements, each playing a crucial role in the overall functionality: (i) the Common Data Environment (CDE), (ii) the Outdoor AR Registration Engine, (iii) the Indoor AR Registration Engine, and (iv) the Switch Engine (Fig. 1). The BIM Cloud Platform serves as a centralized resource and processes hub that facilitates data processing, storage, and distribution. An important characteristic of the platform is its ability to host, localize, and align BIM models, images, and point clouds within a geospatial context. This geolocation feature enables the precise mapping of virtual assets and features to their corresponding real-world locations, facilitating the integration between the virtual and physical realms. One of the key responsibilities of the BIM Cloud Platform is therefore to manage the alignment processes. Particularly, the positioning of images within the platform is achieved by referencing the absolute world coordinates of the acquisition point, along with the accurate rotations. This process ensures that images (and point clouds) are precisely georeferenced and aligned to their real-world locations. This approach lays the foundation for understanding the subsequent paragraphs, which delve into the concept of "images in the vicinity of the user's position".

The CDE is responsible for structured (e.g., .ifc files) and unstructured (e.g., images) data storage. It facilitates accessibility to AR applications through dedicated clients. In this work, the CDE of the DICEA Department of the Università Politecnica delle Marche has been used. At its core, a graph database provides a resilient backbone, offering efficient storage, retrieval, and traversal of interconnected data elements. The next integral components are the two distinct registration engines, specialized for outdoor and indoor environments, respectively. The Outdoor AR Registration Engine, which relies on the combination of RTK GNSS and IMU systems, is tailored to tackle the unique challenges presented in open spaces, such as dealing with the absence of reliable reference points and coping with large and dynamic environments. On the other hand, the Indoor AR Registration Engine is designed to excel in environments characterized by restricted access to GNSS signals, leveraging features like point clouds and aligned images to achieve accurate positioning. To this purpose, convolutional neural networks (CNN) (Sarlin, Cadena, et al., 2018; Sarlin, Debraine, et al., 2018) that simultaneously predict local features and global descriptors have been applied for accurate 6-DoF localization. Finally, the pivotal feature of this system lies in the Switch Engine, which effectively serves as an integrator between the outdoor and indoor registration engines. It is a rule-based engine that assesses the availability of either GNSS signals, or features, or both, and dynamically switches between the two registration approaches to maintain a consistent and uninterrupted AR experience. By synergistically combining the aforementioned four elements within the BIM Cloud Platform, the system architecture (Fig. 1) delivers a robust and marker-less AR system that can seamlessly adapt to both indoor and outdoor scenarios (i.e., answer to RQ1). Although the approach and methodology proposed in this paper are applicable to both head-mounted and hand-held AR devices, the focus from this point forward will be specifically on the usage of Microsoft's AR tool, HoloLens2. To this end, a novel addition to the tool is introduced, developed, and physically realized, enabling a robust connection between the HoloLens2 device and the RTK receiver for precise calibration between the systems. The presented system architecture has been implemented in an AR application for HoloLens2 developed using the C# programming language and the serious game engine Unity3D.

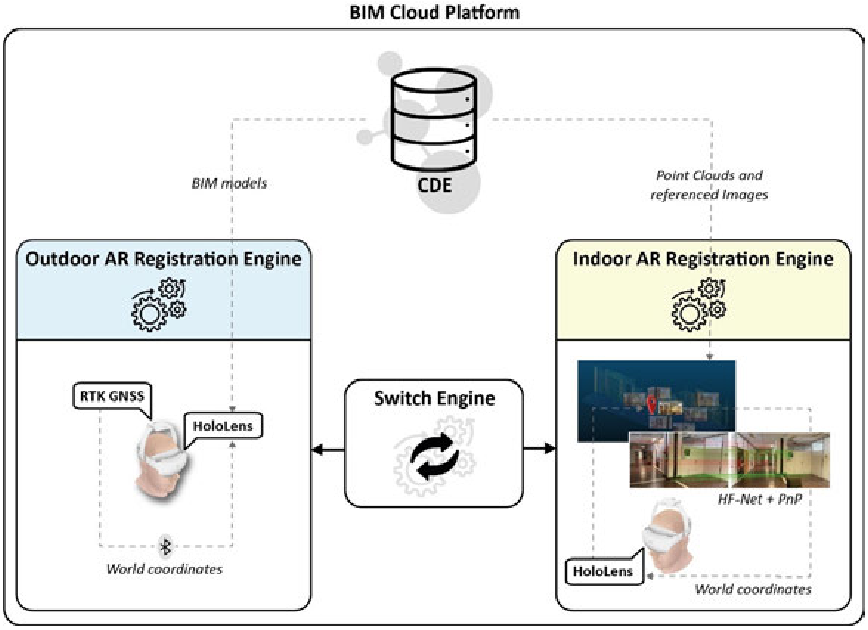


Fig. 1: Architecture of the proposed system for seamless outdoor and indoor AR registration.

3.1.1 Outdoor AR Registration Engine

Following the works made by Hansen et al. (2021) and Ling et al. (2019), the Outdoor AR Registration Engine proposed in this paper relies on the combination of a RTK GNSS tracking system and the HoloLens2' built-in inertial tracking system. By aligning the local frame reference of the HoloLens2 device to global coordinates exploiting the RTK measurements and using the HoloLens2 capability to localize itself in the environment through a real time mapping service, a geographical SLAM algorithm can be developed in order to have an absolute 6-DoF localization of the AR device and therefore aligned virtual objects. Some considerations must be made:

- a general 3D object in the BIM Cloud Platform has its own reference frame located in the world that is fully specified by its geographical coordinates and its orientation with respect to the North: Latitude (°), Longitude (°), Altitude (m), and Azimuth (°). Object's coordinates refer to the WGS-84 standard;
- the coordinates retrieved from the RTK system are based on the WGS-84 standard;
- the RTK receiver has been developed in-house with contained costs in the perspective of widespread adoption;
- the RTK receiver and the HoloLens2 must be solidly connected to each other;
- the RTK system is reliable as long as the receiver is within 10 km of the RTK base station antenna;
- the HoloLens2' local coordinate frame originates at the point where the AR application is turned on.

The problem of placing world-referenced 3D BIM objects into the HoloLens2 local frame can be achieved by fulfilling the following steps (Fig. 2): (i) aligning the local frame with the North direction, (ii) adjusting the object position, (iii) adjusting the object altitude, and (iv) placing objects based on the distance from the observer. The resulting Outdoor AR Registration Engine's process (Fig. 2) is automatically executed (i.e., answer to RQ2). Hence, the outdoor registration process, not requiring any particular action from the user, can find applicability even among non-expert users.

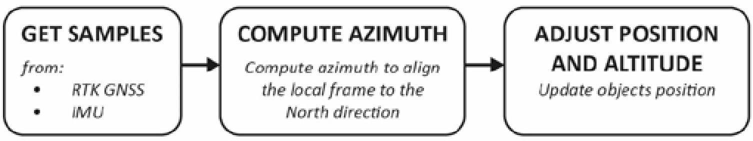


Fig. 2: A schematization of the outdoor AR registration engine's processes.

The first part of the outdoor engine involves the initialization phase of the HoloLens2 position. It includes acquiring initial samples from both the RTK and IMU systems. Once initialized, the RTK system provides absolute 3D coordinates of the body frame (Latitude φ_1, Longitude λ_1, and Altitude h_1), while the IMU provides for local 3D coordinates (x, y, z) and rotations of the body frame. The local equirectangular projection must have y axis directed toward the North. However, at the beginning, the HoloLens2' local frame has an arbitrary unknown orientation with respect to the North. To solve this, when moving between two positions, the performed segment has an orientation β' with respect to the y' axis but the same movement forms a bearing angle β with respect to North as shown in Fig. 3.

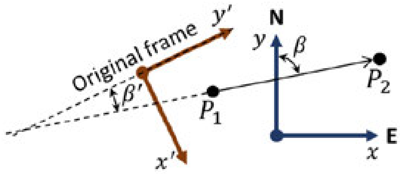


Fig. 3: Bearing angles with respect to North direction.

Given latitude and longitude of the start point (φ_1, λ_1) and latitude and longitude for the end point φ_2, λ_2 of a straight line along a great-circle area, the initial bearing (sometimes referred to as forward azimuth) can be computed as follow:

$$\beta = atan2\left(\frac{sin(\lambda_2-\lambda_1)cos(\varphi_2)}{cos(\varphi_1)sin(\varphi_2)-sin(\varphi_1)cos(\varphi_2)cos(\lambda_2-\lambda_1)}\right) \tag{1}$$

The geographical position of its reference frame (φ_0, λ_0) can be computed by inverting the reverse projection:

$$\lambda_0 = \lambda' - \frac{x}{Rcos\varphi_1} \tag{2}$$

$$\varphi_0 = \varphi' - \frac{y}{R} \tag{3}$$

assuming that $\varphi_0 = \varphi_1$ and where (φ', λ') are the GNSS coordinates and R is the radius of the globe. When the local frame position (φ_0, λ_0) and the object's geographic coordinates (φ'', λ'') are known, the corresponding local planar coordinates can be computed by the forward projection:

$$x = R(\lambda'' - \lambda_0)cos\varphi_1 \tag{4}$$

$$y = R(\varphi'' - \varphi_0) \tag{5}$$

When the observer moves too far from the origin, the local reference should be translated in the new position and the 3D objects must be positioned with respect to the new reference system by re-applying the previous equations. To track the true value of the observer altitude, each time a GNSS measure is acquired for the observer's altitude h', its height in the local coordinate system can be stored for later use as height of the origin of the local frame. Consequently, given the altitude of the local frame (h_0), its height in local coordinates z_0 and the altitude of an object (h''), the corresponding vertical coordinate z of an object can be computed by:

$$z = h'' - h_0 + z_0 \tag{6}$$

If the observer vertically moves the objects at z' to match their true height from the ground, the resulting true altitude is computed and stored. When the observer moves too far from the origin, the local reference should be vertically translated in the new altitude and the 3D objects must be positioned with respect to the new reference system by re-applying the previous equations.

3.1.2 Indoor AR Registration Engine

The AR registration in indoor environments, which contrarily to the outdoor ones are affected by restricted GNSS signals, required a dedicated solution different from the one presented in Section 3.1.1. For this reason, an Indoor AR Registration Engine, based on image comparison with survey data of the analyzed environment, has been developed (Fig. 4). A preliminary on-site survey with a camera and LiDAR scanner (e.g., GeoSLAM ZEB Horizon) must be carried out in order to collect point cloud and aligned photos of the analyzed environment. Alternatively, point clouds can be generated from a photos collection using the incremental Structure-from-Motion methodology implemented by the COLMAP library (Schönberger & Frahm, 2016). The basic idea is 6-DoF localizing the HoloLens2 by comparing a frame from its current view (i.e., query image) with images referenced to the point cloud of the analyzed environment (i.e., reference images). Both reference images and the point cloud are stored in the BIM Cloud Platform. In this study, the Hierarchical Feature Network (HF-Net) technology has been implemented for image comparison (Sarlin, Cadena, et al., 2018; Sarlin, Debraine, et al., 2018). HF-Net consists of a CNN able to simultaneously detect feature keypoints and compute local and global descriptors for accurate 6-DoF localization. The "hierarchical" attribute refers to the HF-Net feature close to the humans' attitude of naturally localizing, in a previously visited environment, with a "from coarse to fine" approach. In other words, humans first localize themselves by looking at the global scene appearance and subsequently inferring an accurate location from a set of likely places using local visual clues. This means that for each HoloLens2 registration call, a coarse search, consisting in a global-descriptors matching between the query image and the reference images, is performed. Afterwards, a finer search based on a local-descriptors matching between the query image's 2D keypoints and the point cloud's 3D points covisibile in reference images is executed. Finally, a 6 DoF pose estimation of the query image is carried out by solving the Perspective-n-Point (PnP) problem (Kneip et al., 2011). The estimated pose is thus the rotation and the translation vectors that allow transforming 3D points expressed in the world coordinate system into the camera coordinate system. These parameters enable the indoor AR registration of HoloLens2's gaze.

The presented Indoor AR Registration Engine's process (Fig. 4), once the survey of the interested area is completed, can be automatically executed (i.e., answer to RQ2). Hence, the indoor registration process, not requiring the user to do any particular actions, can find applicability even among non-expert users.

Fig. 4: A schematization of the Indoor AR Registration Engine's processes.

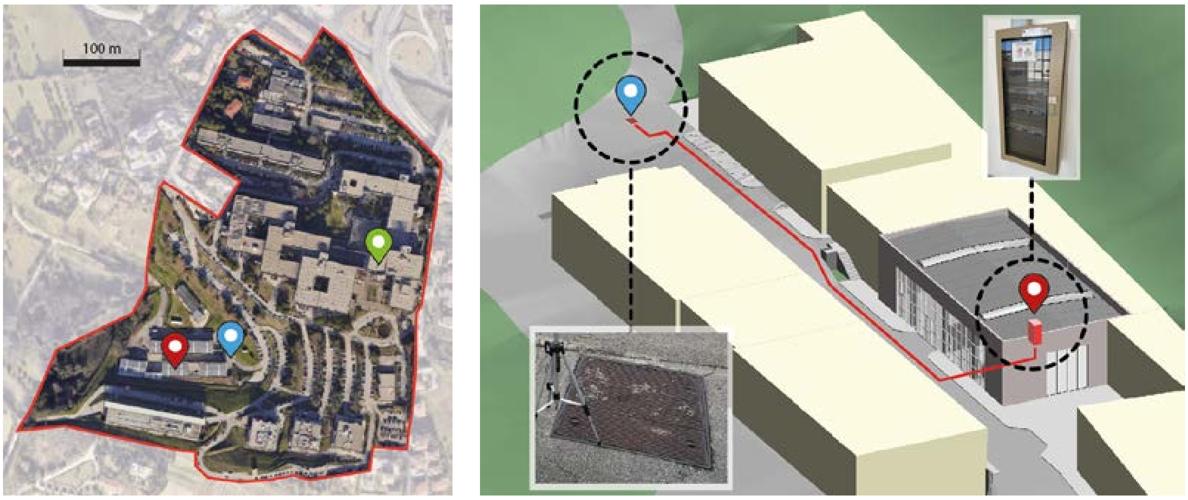
3.1.3 The Switch Engine

As illustrated in Fig. 1, the Switch Engine serves as a seamless integrator between the two types of registration, contributing to answer both RQ1 and RQ2. This component is a rule-based engine that enables seamless indoor/autdoor AR registration. The Switch Engine acts differently according to 3 possible scenarios: (i) RTK only (outdoor), (ii) RTK plus images/point clouds (outdoor), and (iii) images/point clouds only (indoor). In the first scenario, the Switch Engine identifies the availability of a stable and reliable RTK connection in outdoor scenarios. Consequently, the Switch Engine triggers the outdoor AR Registration Engine. The second scenario occurs when, in outdoor environments, images and point clouds are available simultaneously with RTK connection. The third scenario, instead, refers to indoor scenarios in which only images and point clouds are available. In both the second and third scenarios, as the Switch Engine identifies the presence of images and point clouds in the vicinity of the user's real-world position (e.g., when approaching a previously surveyed building or asset), the system triggers the Indoor AR Registration Engine. At that point, the system entirely relies on images and point clouds for AR registration.

4. EXPERIMENTS

4.1 FM use case

The methodology proposed in this study has been tested on a FM use case based on a university campus, assumed as case study. Specifically, the study focused on the FM of the Digital Construction Capability Centre (DC3) Lab at the Università Politecnica delle Marche (Fig. 5 (a)). The DC3 Lab, which covers an area as large as 240 m^2, is composed of a main open space, a changing room, an office, and the restroom. Within this context, the management of the electrical system, and in particular of the internal electrical panel of the DC3 Lab, has been considered. During this activity, the technician in charge of FM operations spends time first locating the electrical panel. Then, in order to find the root cause of the problem, the technician may be asked to locate the panel's associated cabling, which extends externally to the building. These cables can be accessed through manholes located on the road in front of the building (Fig. 5 (a)). Once located all the elements interested by FM operations, the technician may need technical information about the electrical system. To this purpose, he/she needs to access the as-built BIM model (Fig. 5 (b)). The implementation of the proposed methodology (Section 3) enables the seamless AR registration in heterogeneous indoor/outdoor scenarios. Testing the proposed system to the presented use case, its applicability in real-life situations will be assessed. As described more in detail in Section 4.2, the experimentation primarily revolves around the utilization of an AR application implemented on the HoloLens2 device.



(a) (b)

Fig. 5: (a) Aerial view of the university campus, assumed as case study, identifying the positions of the DC3 Lab (i.e., red placemark), the manhole cover (i.e., blue placemark), and the RTK base antenna (i.e., green placemark); (b) view of the BIM model of the DC3 Lab identifying the positions of the indoor electrical panel (i.e., red placemark) and the outdoor manhole cover (i.e., blue placemark).

4.2 Experiments design and execution

The developed system has been tested on the selected use case (Section 4.1) following the steps summarized in this section. First of all, a preliminary set-up phase consisting in collecting and initializing input data has been executed. This phase must be executed only once since related input and settings are maintained. It includes:

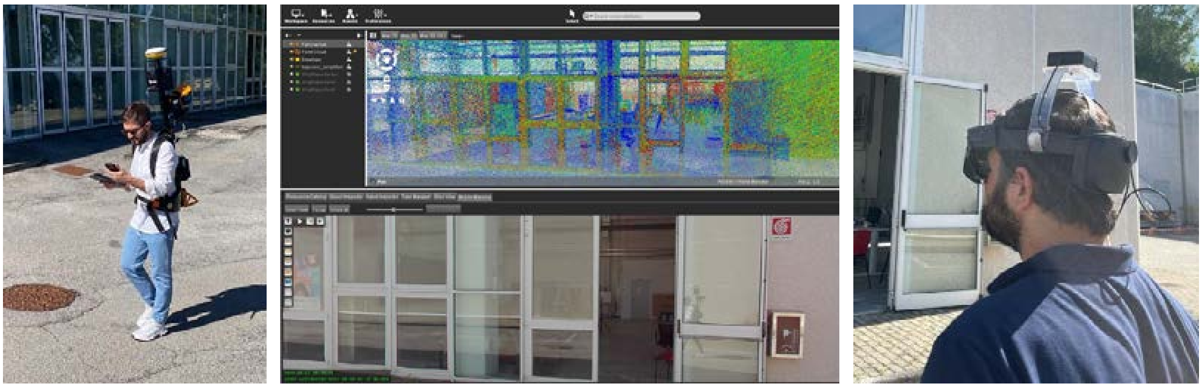
1. collecting point clouds and aligned photos by carrying out a survey of the DC3 Lab. In this study, the survey has been carried out by using GeoSLAM Backpack Vision (Fig. 6 (a)), which collects simultaneously both point clouds and aligned photos with a single scanning (Fig. 6 (b)). Alternatively, the survey can be carried out by collecting photos (e.g., with a smartphone) and then generating a point cloud through the Structure-from-Motion methodology implemented by the COLMAP library (Schönberger & Frahm, 2016);
2. collecting the BIM model of the DC3 Lab (Fig. 5 (b));
3. uploading the BIM model, point cloud, and images, related to the selected use case, on the BIM cloud platform. It must be noted that point cloud and images result aligned directly from the survey. The BIM model must be aligned to the previous dataset by selected reference points; it must be noted that this alignment is executed only once since it is maintained.

Once the previous preliminary steps are completed, the AR-based inspection of the electrical system related to the selected use case can start. In this study, the head-mounted AR device Microsoft HoloLens2 has been used (Fig. 6 (c)). The AR application, based on the system architecture reported in Fig. 1, has been developed to support the technician inspecting the electrical system distributed in a heterogeneous indoor/outdoor scenario. The main contribution of the proposed system is the marker-less AR registration for displaying BIM models seamlessly superimposed to the whole inspected environment. The following steps have been executed on-site:

4. having on the HoloLens2 with installed RTK receiver (Fig. 6 (c)) and launching the AR application;
5. moving around the campus of the Faculty of Engineering at Università Politecnica delle Marche. During this preliminary step outside the DC3 Lab, the Outdoor AR Registration Engine is triggered in order to localize the user and drive him/her to the DC3 Lab;
6. heading to the internal electrical infrastructure to inspect the electrical panel located inside the DC3 Lab (Fig. 5 (a)). As the user moves from the outdoor to the indoor, the GNSS coverage decreases and the collected dataset (i.e., point clouds and aligned images) is found in the surrounding of the user position. Hence, the system seamlessly switches to the Indoor AR Registration Engine. This transition occurs without interruption as the system switches between registration modes through the Switch Engine's algorithm;
7. inspecting the internal electrical infrastructure, specifically focusing on the indoor electrical panel. During the

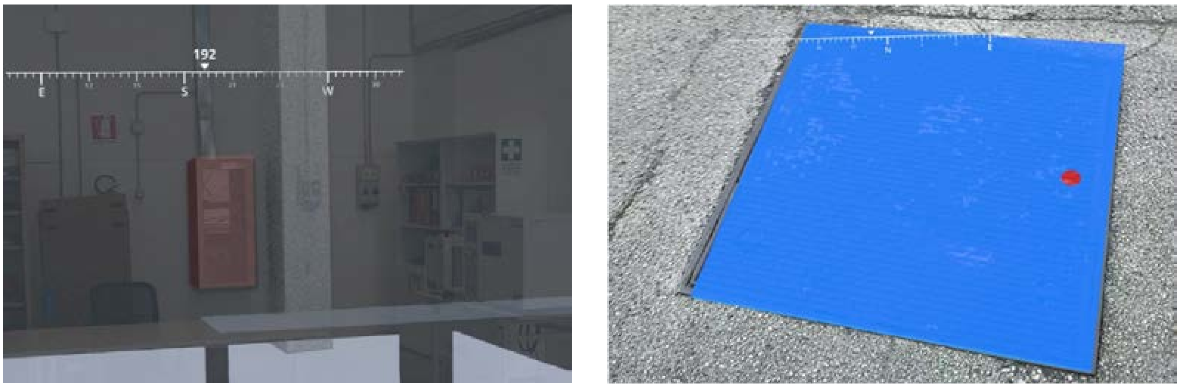
indoor phase, the AR application relies on the Indoor AR Registration Engine. It superimposes the digital model of the electrical panel on the real asset to let the facility managers have all the required information from the BIM model for the inspection (Fig. 7 (a));

8. heading to the external electrical infrastructure to inspect the cablings associated to the internal electrical panel. As the user moves from the indoor to the outdoor, the GNSS coverage rises again and the system seamlessly switches to the Outdoor AR Registration Engine. This transition occurs without interruption as the system switches between registration modes through the Switch Engine's algorithm;
9. inspecting the external electrical infrastructure, specifically focusing on the manhole covers located on the street facing the building (Fig. 5 (b)). During the outdoor phase, the AR application relies on the Outdoor AR Registration Engine, leveraging geospatial data retrieved from the RTK receiver to overlay BIM data on the real asset (Fig. 7 (b)).



(a) (b) (c)

Fig. 6: (a) Survey phase of the DC3 Lab by using GeoSLAM Backpack Vision for collecting (b) point clouds and aligned photos; (c) inspection phase with the Microsoft HoloLens2 and the RTK receiver integrated by a 3D printed add-on.



(a) (b)

Fig. 7: Visualization of the aligned holograms of (a) the indoor electrical panel and (b) the outdoor manhole cover through the AR application deployed on Hololens2.

5. DISCUSSION AND CONCLUSIONS

This paper addresses the open issue of AR registration in mixed scenarios considering that indoor-outdoor interactions are crucial for built environment management. An extended literature review has found limitations of existing indoor and outdoor AR registration approaches, drawing the conclusion that an all-in-one solution conceived for heterogeneous scenarios do not exist yet. Hence, this work focuses on defining and implementing a system architecture for seamless AR registration even during changes in environment (i.e., RQ1). In doing this, technical solutions that would make AR registration applicable even among non-expert users have been considered (i.e., RQ2). In order to answer RQ1, a system architecture (Section 3.1), which delivers a robust and marker-less AR registration system for both indoor and outdoor scenarios, has been defined and implemented. The resulting system has been tested on-site on a FM use case (Section 4.1). The proposed marker-less localization system has been put in place considering the FM of a university laboratory's electrical system. It has been selected because in-charge technicians and facility managers are continuously asked to locate, inspect, and repair interrelated system elements distributed in a heterogenous indoor/outdoor environment. Efficiency of such activities is expected to be considerably improved by accessing BIM models directly superimposed to their physical counterparts. In this study, the head-mounted AR device Microsoft HoloLens2 has been used for 6DoF localization and seamless gaze registration in heterogeneous environments. Indoor inspections of the electrical system have specifically focused on the laboratory electrical panel, whereas the outdoor ones on the related cablings that can be inspected through a dedicated manhole cover. The proposed system has shown promising results in registering the BIM model on-site. In fact, the holograms of the electrical panel and the manhole cover resulted superimposed to their physical counterpart even if they are located respectively in indoor and outdoor environments. This has confirmed one of the main contributions of the proposed system, that is a marker-less AR registration for displaying BIM models seamlessly superimposed to the whole inspected environment. In order to ensure a user-friendly AR registration process in mixed environments, hence providing an answer to RQ2, the proposed system requires only a preliminary set-up phase (i.e., steps 1-3 in Section 4.2) whose settings are then maintained. In fact, as confirmed by experiments, the AR experience is supported by the Switch Engine that manages priorities of the indoor and outdoor AR registration engines. In areas with GNSS coverage (i.e., generally outdoor environment), the Switch Engine delegates holograms superimpositions to the Outdoor AR Registration Engine. This is the logic that regulates the superimposition of the external manhole cover hologram to its physical counterpart. As the GNSS coverage is lost and collected datasets (i.e., point clouds and aligned images) are found in the surrounding of the user position (i.e., generally indoor environments), the Switch Engine delegates holograms superimpositions to the Indoor AR Registration Engine. This is the logic behind the superimposition of the internal electrical panel. As a result, since AR registration is automatically fulfilled in heterogeneous environments, the proposed solution can find applicability even among non-expert users.

Current limitations of the proposed methodology can be traced back to technologies adopted by system's engines. Accuracy loss may affect image comparison, adopted by the Indoor AR Registration Engine, in case of reference and/or query images with lack of context or repetitive elements. Follow-up studies may quantify such limitation. On the other hand, the Outdoor AR Registration Engine strongly relies on the availability of RTK coverage. Despite such technology is currently economically expensive, it is noteworthy that since the individual components of RTK systems are economically affordable, the proliferation of applications of this technology is highly expected. Further studies will be carried out in order to assess registration accuracy of both the Indoor and Outdoor AR Registration Engine. More tests must be carried out in order to optimize switching thresholds based on GNSS coverage and datasets (i.e., point clouds and aligned images) availability in the surrounding of the user position. Future developments will focus also on the definition of a graphical user interface for better managing the entire AR registration workflow. Finally, the proposed system will be provided to non-expert users in order to quantify its contribution in terms of saved time for completing a task.

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INTEGRATING REAL-TIME OBJECT DETECTION INTO AN AR-DRIVEN TASK ASSISTANCE PROTOTYPE: AN APPROACH TOWARDS REDUCING SPECIFIC MOTIONS IN THERBLIGS THEORY

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ABSTRACT: Due to challenges in filling vacant positions and the heightened demands posed on existing staff, employers and project managers are progressively considering the recruitment of inexperienced individuals and seeking strategies to swiftly provide them with essential job-specific knowledge. The potential of industrial AR has been widely researched to support workers in overcoming skill-related knowledge and enhancing industrial processes. However, most studies focus on demonstrating technology usability across different processes and overcoming engineering hurdles on a case-by-case basis. There is no direct benefit analysis on how AR assists construction tasks at human motion level, and how to eliminate the ineffective motions and reduce the duration of effective motions. To fill this gap, this paper first establishes an AR-based near real-time object detection system of small tools and components involved in task processes for egocentric perception of workers in the construction industry. Later, the Standard Operating Procedure (SOP) for scaffolding assembly activities is deconstructed from a manual process into Therbligs-based elemental motions. Finally, this research conducted a comparative study of two prototypes across four dimensions of evaluation. As a step forward in this direction, this paper renews the connotations of Therbligs theory under industry 5.0 era, rethinks the AR-assisted construction task processes, and applies appropriate technologies enhancing the adaptability of AR technology for construction workers' needs.

KEYWORDS: *Augmented Reality (AR); Microsoft HoloLens 2; Object Detection; Task Assistance; Therbligs*

1. INTRODUCTION

The construction industry, characterized as one of the least digitized and toughest labor challenges, urgently seeks solutions for industry transformation (Liao, Iseley, & Behbahani, 2022). In Canada, nearly half of the construction employers are facing the obstacle of recruiting skilled employees over the next three months (Government of Canada, 2022). Meanwhile, increased project complexity implies a high degree of technical, organizational and environmental variability and uncertainty, which leads to greater risk and poorer performance by construction personnel (Peñaloza, Saurin, & Formoso, 2020). In terms of technical requirements alone, project contributors must possess a more reliable and advanced technical qualification (Trinh & Feng, 2020). From the organizational and demographic characteristics, most construction workers rather rely heavily on previous work experience or oral interpretation from peers than follow the correct mechanical operation steps or standardized operation procedure (Ke, 2018). Oyekan et al., propose one of the mental challenges faced by workers, highlighting that as task operations become more complex, the cognitive load on operators also intensifies. This heightened cognitive load can be reflected in various human mental reactions of "Search," "Find," "Select," and other Therbligs. Consequently, due to the greater difficulty in filling vacant positions and the increased demands placed on employed personnel by the complexity of construction projects, employers and project managers are gradually hiring inexperienced newcomers and are eager to find countermeasures to equip them with the necessary job-related knowledge in a short time (Büttner, Prilla, & Röcker, 2020).

Industrial AR, deploying Augmented Reality (AR) technology into dynamic industrial environments targeting inhomogeneous user groups, is seen as potential solution to above dilemma and gains more momentum in both academic and industry (Grubert et al., 2010). The potential of Industrial AR has been widely researched to support workers in industrial scenarios in overcoming skill-related knowledge and enhancing industrial processes (de Souza Cardoso, Mariano, & Zorzal, 2020). In the context of industrial AR, one of the more fruitful and practical projects is the AR-Driven Task Assistance system, which supports workers by providing real-time sequence of assembly operations, tools to be used and collision free assembly paths at the workplace (Eswaran & Bahubalendruni, 2022). Previous research and the authors of this paper have also contributed to the development

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Xiang Yuan, Qipei Mei, Xinming Li, *Integrating Real-Time Object Detection into an AR-Driven Task Assistance Prototype: An Approach Towards Reducing Specific Motions in Therbligs Theory,* pp. 121-132, DOI 10.36253/979-12-215-0289-3.12

of a similar task-assisted AR prototype, which in this paper is expected to focus on the second function for highlighting recommended tools in the user's view while performing a task. Oyekan et al. addressed the mentioned challenge by using Therbligs to embed intelligence in workpieces and make them interactable and communicable. They developed smart workpieces to actively participate in assembly operations by providing their location and operational sequence to an operator (Oyekan et al., 2020). However, their solution may encounter various practical issues, such as overloaded servers when many workpieces update their status simultaneously, mispositioning of sensors and LEDs leading to electronic faults, and greater weight and more challenging manipulation of workpieces due to the addition of extra components.

It is obvious that CV and AR are theoretically linked and mutual fulfillment of each other, as OD could quickly identify and localize specific objects and draw bounding boxes around instances, and AR greatly extends users' capability and experiences by directly presenting detected objects and their digital data in an immersive, interactive way (Z. Wu, Zhao, & Nguyen, 2020). Thus, this paper proposes another computer vision-based solution to the same challenge by integrating OD into an AR-driven task assistance prototype. The choice of deployed technologies is highly related to their ability and referred to prior successful cases. While researchers have established the effectiveness of Industrial AR and its widespread adoption in construction task assistance over the past two decades, most studies focus on demonstrating technology usability across different processes and overcoming engineering hurdles on a case-by-case basis (Kim, Olsen, & Renfroe, 2022; S. Wu, Hou, Zhang, & Chen, 2022). However, user-related assessment of AR assistance systems and worker-oriented effectiveness in industrial environments is not a major focus (Tao, Lai, Leu, Yin, & Qin, 2019). To be more specific, there is no direct benefit analysis of how AR assists construction tasks at the human motion level and how to eliminate ineffective motions and reduce the duration of effective motions.

To fill this gap, this research first reports the further exploration of embedded object detection into the existing AR-driven task assistance prototype developed by authors. The existing AR prototype is targeted at construction workers without any previous work experience to conduct tasks from the beginning. But it only provides fixed information designed in advance about the activities and corresponding contents step by step. More advanced, the prototype developed in this research realizes a real-time detection of multiple scaffolding components, superimposes holographic texts, and gives hints about the correct selections which helps new industry entrants make the right choices from a wide range of tools and components. Later, the Standard Operating Procedure (SOP) of scaffolding assembly activity is decomposed from a human manual process into Therbligs-based elemental motions. It serves as both a specific example to enhance the understanding of Therbligs-based task processes and the foundation of subsequent benefit analysis. To present a more intuitive and clear effect, this research finally adopted a comparative study of a traditional AR prototype and an advanced AR prototype with object detection function from four dimensions of evaluation. It will demonstrate the superiority of the proposed prototype in easing cognitive load, eliciting contextual awareness, and reducing particular motion costs on Search, Select, and Find.

The proposed pathway not only explores the possibility of fully exploiting the advantages of both Augmented Reality and Object Detection, but also allows novice workers to easily perform high requirements tasks with a satisfied completion accuracy. As a step forward in this direction, this paper renews the connotations of Therbligs theory under industry 5.0 era, rethinks the AR-assisted construction task processes, and applies appropriate technologies enhancing the adaptability of AR technology for construction workers' needs. It is expected this research could inspire substantial discussions, enhance the implementation of AR-driven task assistance, and provide a valuable reference for construction workforce preparation.

2. RELATED WORK

2.1 Therbligs overview

Therbligs, first invented by Frank Gilbreth during the early 20th century, is a collection of 18 elemental human mental and physical motions used to describe any task and analyze the motion economy in the workplace (Sung, Ritchie, Lim, & Medellin, 2009). The full collection of 18 Therbligs and their symbols used for depicting when performing work is shown in Table 1. It is useful to use Therbligs to analyze the impact of technology adoption on individual earnings (Wang et al., 2021). The overall efficiency and productivity of tasks will be significantly improved because less time wasted on non-value-added activities and more time spent on productive work. The selection of Therbligs to be analyzed and addressed in this paper is not random. Taking consideration of the capabilities of computer vision technology and extended understanding of Therbligs connotation in the context of the construction tasks, this research mainly focuses on elemental motions of "Search", "Select" and "Find", which is also complied with previous research of Oyekan et al. The description of chosen Therbligs and their connotation in the context of the construction industry could be found in Table 2, gathering previous research and examples mentioned in the conversation with experts in both the ergonomics field and construction industry (David, 2000). For the application scenarios in this research, object detection function will be deployed to reduce the efforts needed by construction workers to search and select the tools and components they need.

Table 1: 18 Therbligs with symbols (Ninjatacoshell, 2012)

Table 2: Description of chosen Therbligs and their connotation in the context of the construction industry

Therbligs	Symbol	Description (Niebel & Freivalds, 2013)	Examples in the construction activities
Search	S	Eyes or hands groping for object; begins as the eyes move in to locate an object.	A construction worker looks for the location of a hammer in a warehouse.
Select	SE	Choosing one item from several; usually follows Search.	A construction worker selects the appropriately sized steel beam from a range of options.
Find	F	Defines the momentary mental reaction at the end of the Search cycle.	A construction worker realizes that he had found the correct 5 mm drill.

2.2 AR for Worker Onboarding and Skill Development

Industrial AR related to worker onboarding and skill development typically falls into two categories based on the research purposes and system functions: Step-by-Step Assistance AR and Hands-on Training AR (Butaslac, Fujimoto, Sawabe, Kanbara, & Kato, 2022). Both systems essentially start from the premise of breaking down knowledge barriers for people who do not have the ability or experience to perform the task contents. The difference between them is Hands-on Training AR will emphasize more on the knowledge stock after using the system and the ability to work independently when users are not equipped with system (Büttner et al., 2020), while Step-by-Step Assistance AR will emphasize the prompts, flexibility, and adaptive to users' needs and facilitate quicker familiarization and more regulated execution of predetermined task procedures (Zhang, Xuan, Yadav, Omrani, & Fjeld, 2023). For the user groups and specific scenarios targeted in this paper, the system built can be categorized as a Step-by-Step Assistance AR system.

2.3 Object Detection for AR

Numerous papers have extensively explored the applications of AR and OD within the construction industry, individually. From data preparation for construction objects, the traditional object detection dataset in the construction context is a collection of various categories (e.g., materials, workers, and their behavior of wearing PPE or falling from height), messy site layout, and large objects (e.g., heavy equipment of crane, excavators, bulldozers, and backhoe diggers). Thus, this research establishes a near real-time object detection dataset for small tools and components involved in task processes for workers' egocentric perception in construction industry. Besides, there exists relatively limited progress in cross-studies of AR and OD in this industry, despite its potential for significant advancement and promising opportunities. Wu et al. measured the utility and effectiveness of AR warning system on onsite construction workers with object detection for tracking onsite workers' locations and dynamic hazard areas (S. Wu, Hou, & Chen, n.d.).

Meanwhile, several other industries, such as smart manufacturing, have conducted successful research on the integration of AR and OD, which can serve as valuable points of reference for further exploration in the context of construction industry. They highlighted possible computing pathways, which could be broadly categorized based on where the data are handled into server-side processing, running locally on the device, or both (Ghasemi, Jeong, Choi, Park, & Lee, 2022). Considering the trade-offs between computational requirement and device limitation, cost and latency tolerance, and network connectivity, this research will adopt Microsoft Azure Custom Vision library as it offers a complete high-level solution suiting for HoloLens computing capabilities and is more common for implementation (Łysakowski et al., 2023).

Several publications investigated the utilization of Microsoft HoloLens 2 along with Azure Custom Vision services for object detection for different purposes (PatrickFarley, 2023). George created a training dataset of 215 images for motherboard and RAM in computer assembly task and reached an 80% match score even in varying environments, but also reveals challenges in limited experimental sample of three participants and false positives in similar components (George, 2021). Fuglseth created a proof of concept program for specific objects recognition and text information visualization in users' view with an open-source Microsoft COCO dataset (Fuglseth, 2022). Although this research demonstrated the technical feasibility of general objects detection in daily life, it lacks a specific use-case context and highlights the limitations of single object detection at a time. Casano used 9 specific classes of the COCO dataset and successfully implemented Azure Custom Vision object detector in the HoloLens for assisting and supporting users for better life or easier work style (Casano, 2021). This paper introduced a more mature and customized system by integrating eye motions, gestures, and voice commands, but faced limitations of predictions efficiency and more rigorous evaluation. Their pipelines to realize the object detection function are similar with each other. HoloLens will take a picture based on users' commands and uploads the picture to the Azure Custom Vision API. After successfully identifying, a label or images will be placed in users' AR view for easier awareness. These studies underscore the growing significance and feasibility of object detection in AR applications, point out challenges associated with their specific applications, and also highlight the potential for further improvements. It includes realizing a real-time object detection, testing its usability in practical application scenarios of industrial tasks, and developing a more powerful AR system to support more reliable multi-objects detection results.

3. PROTOTYPE DESIGN AND DEVELOPMENT

3.1 Prototype Overview

The fundamental idea behind the envisioned prototype involves the utilization of HoloLens 2 as an aiding instrument for promptly identifying objects in near-real time. Its primary function is to aid workers in identifying the precise tools and components required for the ongoing task phase. The target users for this prototype comprises generic individuals who lack prior work experience but seek rapid acquaintanceship with task-related details to ensure adherence to standards. For example, a novice construction worker aims to efficiently select tools and components aligned with the day's designated task and make high-quality commitments to their work activities. The object detection function will be triggered by users' voice commands, touch buttons, or gestures. The objects will be identified according to the current task step and its mentioned tools or parts. Once related objects are successfully recognized, the list of expected results will be three main parts (Farasin, Peciarolo, Grangetto, Gianaria, & Garza, 2020). A bounding box is a rectangle area that represents the object and its region. The class is a tag of the most probable category that the object belongs to. The probability score is the confidence level of algorithms in the detection accuracy and serves as a critical criterion for accepting or rejecting results. All information included will be displayed in the AR view as a visualized cue to workers.

3.2 Hardware and Software

Trimble XR10 with HoloLens 2 - Full Brim Hardhat is an integrated device in which a construction hard hat ensures easier wireless use in safety-constrained environments and the HoloLens 2 is the most commonly used XR headset. Microsoft HoloLens 2 is an ideal platform with high-tech hardware features for computer vision research, and also provides scalability of cloud services and connection to Microsoft Azure AI platform (Ungureanu et al., 2020). It sets a suitable equipment base that could serve multiple roles in proposed research and subsequent research, such as the source for capturing data in the form of video and frames, a computer of executing detection functions, and the tool for visualizing processed data and related task information (Qin et al., 2023). The proposed prototype is developed in the Unity cross-platform graphics engine (version 2022.3.3f1 LTS) using C# as programming language and MRTK (Mixed Reality ToolKit) packages for assets and interactive UI creation. Currently, this research adopted Microsoft Azure Cognitive Services to deploy object detection function by using

REST APIs and client library SDKs.

3.3 Object Detection using Azure Custom Vision in HoloLens

Microsoft Azure Custom Vision services enable users to rapidly customize cloud-based computer vision models and simply manage it using REST API calls. The overall design of architecture is shown in Figure 1. This research created the computer vision project in Azure Custom Vision portal and labelled a total of 12 classes including 1,224 images and 2,008 objects. The training model and its performance is further illustrated in both Section 4.4 and Section 5. The AR application, developed in Unity, adopted MRTK for user interaction and established a connection to the Azure Custom Vision API through endpoints. The Azure platform authenticates the AR system using Azure credentials and provides external GPU computational capabilities to preprocess the images and send the response through Wi-Fi. Once HoloLens receives object detection results from Azure Custom Vision, display holograms or annotations in the user world to indicate the detected objects.

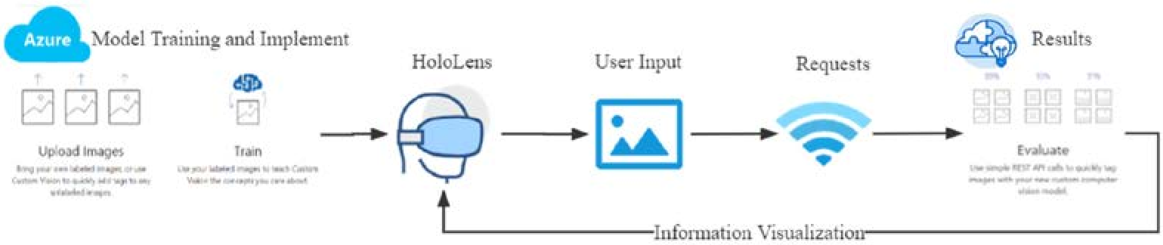


Figure 1 Pipeline design of using Azure Custom Vision and HoloLens 2

4. EXPERIMENT DESIGN FOR EVALUATION

The purpose of designing experiments is to provide a comprehensive insight into whether different forms of AR and varying technologies involved might impact user performance on the motion level. This study is designed with two independent variables: the complexity of construction tasks and the assisted tools used by participants to accomplish these tasks. Each variable is further subdivided, as task complexity has two levels (referred to as Task 1 and 2 hereafter), and using task-assisting tools comes in two types. Task 1 of the Miter Saw Stand assembly is the most complicated to build due to all the extra pieces and steps participants need to follow to make it work properly. Task 2 of the Scaffolding assembly is straightforward to understand what the task entails, but it's also easy to assemble it incorrectly and skip steps on some safety details. Detailed descriptions of these task specifications can be found in the subsequent section (section 4.3). The first type of assisted tools is a conventional AR prototype, which presents participants with guided text, images, and videos (referred to as Prototype 1 hereafter). On the other hand, the second type employs a more advanced AR prototype that includes object detection functionality to highlight crucial components for users (referred to as Prototype 2 hereafter).

4.1 Hypotheses

This research is formulated following hypotheses: **H1:** When using Prototype 2, participants were able to make fewer mistakes and complete the task with higher quality. **H2:** When using Prototype 2, participants were able to complete the task more efficiently, spending less time on "Search", "Select", and "Find" Therbligs. **H3:** When using Prototype 2, participants' cognitive demands were lower, and they can obtain better understandability for task contents and unfamiliar tools. **H4:** When using Prototype 2, participants think it is more intuitive, efficient, and enjoyable to use.

4.2 Bias Control

Potential bias and the effects of irrelevant factors, such as participants' familiarity with AR concepts and interaction, existing skills or learning curve, are more or less to interfere with the experiment results. The counterbalancing design principle and within-subject principle are throughout the entire experimental design and adopted controlling measures are stated as follows. Given that participants might have varying levels of proficiency with AR, some individuals are experienced users and developers, while others have a more superficial understanding [21]. Though researchers prepare an illustrative ppt for introducing experiments, explaining the meanings of prototype UI and panel, and briefly showing how to perform the sample tasks using different prototypes, researchers concern 2D-based explanation is less intuitive than real experience with device. Therefore, the prototype provides a comprehensive quick start guide to build perceptual awareness of AR capabilities and narrow knowledge gap among all participants. To mitigate the potential order effects and learning curve, there is also a clear definition of how to assign the participants into groups and decide their starting sequence. All participants will be randomly divided into two Group A and B. Both Group A and Group B will be exposed to two kinds of prototype and operate the same task, assembly Miter Saw Stand in the test phase 1 and assembly Scaffolding in the test phase 2, as shown in Figure 2. The difference between the two groups is Group A will start using Prototype 1 first, then they will shift to Prototype 2 in the test phase 2, while Group B will use two prototypes in reverse order.

4.3 Task Specification and Therbligs-based Information Presentation

As the basis of experiment design, this research selected the Metaltech Multipurpose 4-in-1 6 ft. Baker Scaffold as the specific user case for experiments, as the scaffolding is a typical and normal task in the construction site with higher hazards (Khan, Saleem, Lee, Park, & Park, 2021). Rigorously building up scaffolds is a vital safety management measure and prevents potential serious individual accidents. In terms of task content design, it can also be converted into another form of miter saw stand, which is a routine task for carpentry but different from those steps and used components in scaffolding assembly. Meanwhile, the difference in difficulty levels between the two tasks makes this choice more suitable for designing an experiment. After field assembly by three researchers, they agreed that the miter saw stand was the most complex and difficult to build, while the remaining three types were not as difficult to distinguish. As mentioned in previous section, the effect of decreased physical strength on experimental effectiveness, as well as increasing the difficulty differentiation between two tasks, two researchers worked together to simplify the task of scaffold assembly. Subjects would neither assemble the upper ladder to the lower part to prevent a total shelf height of about two meters, nor would they rotate the assembled shelf up and down. In the step of transitioning between the scaffold and the miter saw stand, they won't flip the entire platform due to its potentially harmful weight and surface area.

Figure 2 Selected Multipurpose 4-in-1 6 ft. Baker Scaffold for Experiment (The Home Depot, 2022)

Figure 3 shows the partial sequence of the assembly scaffold in the form of "Search", "Select", and "Find" Therbligs. The experiment workplace setup is shown in Figure 4, where all components are lying on the ground and a nearby shelf is for PPE equipment. "Search" Therbligs is reflected in locating the same type of tools from numerous building components in the package, such as searching ladders, braces, and locking pins. "Select" Therbligs happens less often than search, which is embodied in choosing the right one from a variety of similar things or alternatives, such as selecting a lower ladder from ladders where the upper ladder is a misleading option for participants (as shown in Figure 5). "Find" Therbligs is a momentary mental activity that is reflected in the participant starting to move on to the next activity, such as the participant grabbing the searched brace and locking it in place using the U-lock kit.

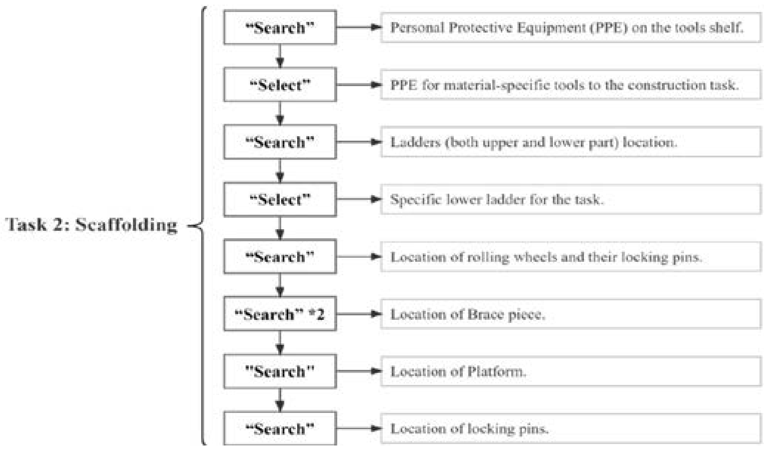


Figure 3 Partial sequence of assembly scaffold in the form of "Search", "Select", and "Find" Therbligs.

Figure 4 Experiment workplace setup.

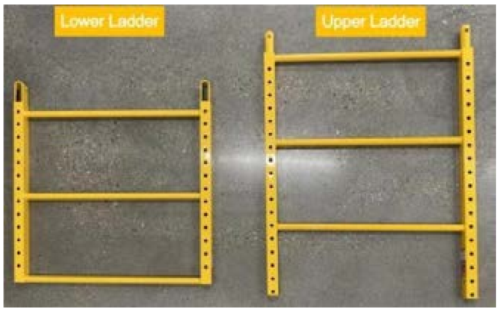


Figure 5 Experiment setting example for “select”.

4.4 Dataset Preparation

High-quality image data for target objects matters a lot to create a robust object-detection model (Lee, Jeon, & Shin, 2023). As shown in Table 3 and Table 4, this present study constructed a dataset to train and test the detection model, which took a total of 1,224 images, including 2,008 objects with 12 categories of classes. The dataset is compiled by two researchers using four devices of Hololens, iPhone, iPad, and Android Phone. This collection covers a diverse range of angles, lighting conditions, and backgrounds, drawing from the environments of two distinct research laboratories. In addition to sufficiently high-quality images of the objects in question, another important thing is the quality and quantity of annotation. The two researchers agreed on the labeling to ensure that the bounding box was strictly around each object. When one researcher’s annotation is complete, another researcher will cross-review each annotation result to ensure consistency. The quantity of each tag is roughly above 120 images, which makes the distribution even and not biased.

Table 3 List of scaffolding components for object detector training

No.	QTY. Used in EXP.	Class	No. Annotated Images
1	2	Lower ladder	137
2	1	Platform	144
3	4	Mounting bracket	194
4	2	Piece support	132
5	2	Brace	147
6	2	Shelf brace	169
7	1	Wire grid shelf (S)	216
8	5	Wire grid shelf (L)	217
9	4	5 in. caster	168
10	10	Locking pin	168
11	2	Anti-tip assembly	183
12	2	Tightening knob	128

Table 4 Examples of Captured Images


1. Lower ladder


2. Platform

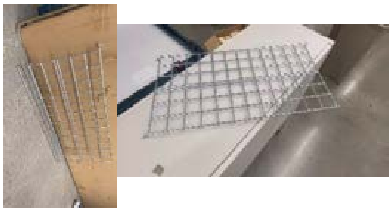

3. Mounting bracket


4. Piece support


5. Brace


6. Shelf brace


7. Wire grid shelf (S)


8. Wire grid shelf (L)


9. 5 in. caster


10. Locking pin


11. Anti-tip assembly


12. Tightening knob

4.5 Procedure and Evaluation Metrics

The overall experiment procedure is shown in Figure 6 an estimated duration of 20-25 minutes. Three GoPro cameras, each at an angle of 120 degrees to each other, were used to record the entire experiment to facilitate the subsequent analysis of the participants' Therbligs-based movements. Each participant will be through four steps: one preparation step, two test steps, and one after-testing step. After both Test Phase 1 and Test Phase 2, participants will be required to fill in a designed after-testing questionnaire immediately to express their direct subjective perception. At the end of the experiment, participants were allowed to volunteer for a short interview to express their opinions on improvements to the system prototype, their willingness to accept the technology, and other feelings not covered in the questionnaire. The data acquisition is based on a four dimensions evaluation: Quality, Efficiency, Mental Demand, and User Experience. The purpose of quality assessment is to detect the degree of precision in the work of the participants. This is done manually by experimental observers and is scored based on a complete error protocol. The error protocol describes errors in detail for two tasks, scores each of the two archetypes, and assigns three levels of scores according to the severity of the error (Wolf et al., 2021). The number of errors and the weighted total error score were finally statistically analyzed. Efficiency can be assessed in two ways. On a macro level, the overall time spent by each participant in completing the tasks using the two prototypes will be compared. On a micro level, experimental observers will use a timer to calculate the duration spent on the motion level of each Therbligs. This paper will explore to what degree user-centered process-oriented object detection has a significant effect on "Search", "Select", and "Find" Therbligs. Mental demand and user experience are mainly obtained through validated questionnaires and supplemented with optional semi-interviews.

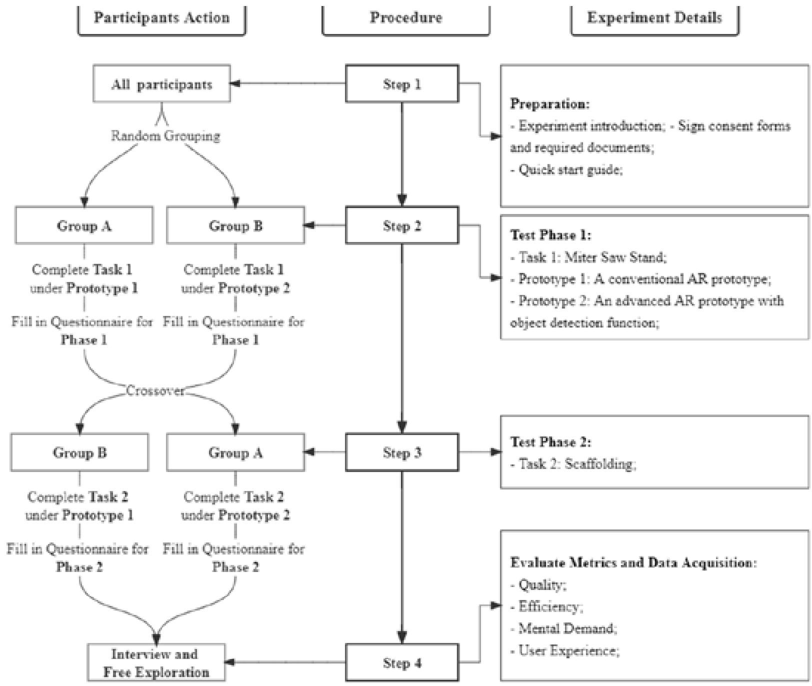


Figure 6 Experimental comparison between conventional AR and advanced AR with object detection

5. OBJECT DETECTION MODEL TRAINING RESULT

After training the model using 3 hours budget with General (compact) domain, the second-iteration training ended with 85.6% precision, 86.4 % recall, and 92% mAP. It is noted that when trying to train for more budget hours, the results remained the same which indicates that object detection model reaches its limitation by using current dataset. These metrics provide critical insights to evaluate the accuracy and effectiveness of object detection models. Precision is how many of the predicted instances are to be actually correct, recall gauges how well the model is capturing all the relevant correct instances, and mAP (mean Average Precision) represents the overall performance. This proposed model has a relatively higher performance in the mAP, which means that the model achieves a good balance between the precision and recall across different thresholds.

The excellent performance of this model is not only reflected in the data metrics, but also in the test images, as shown in . All objects, including very small Tightening Knob and Anti-tip Assembly objects, were successfully recognized one by one with a high success rate of more than 50%. However, there is still room for improvement in this model, as shown in Figure 8. As we mentioned above, we used the upper ladder as a misleading option, allowing participants to select the correct one from the two ladders for subsequent experiments. The trained model was unable to effectively distinguish between the two ladders when recognizing similar ones.

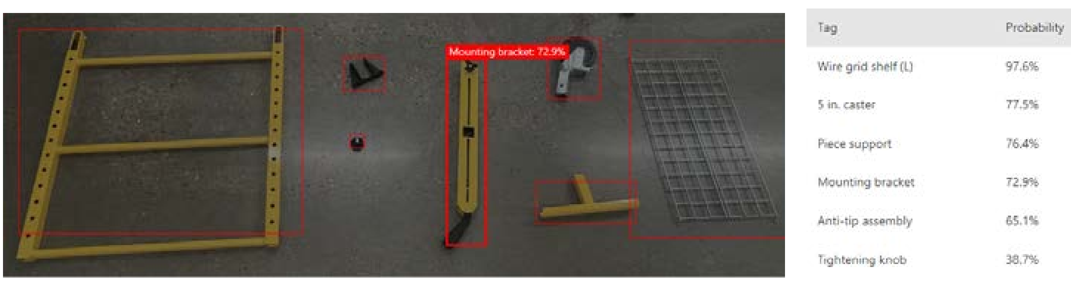


Figure 7 Examples of Object Detection Results from developed model

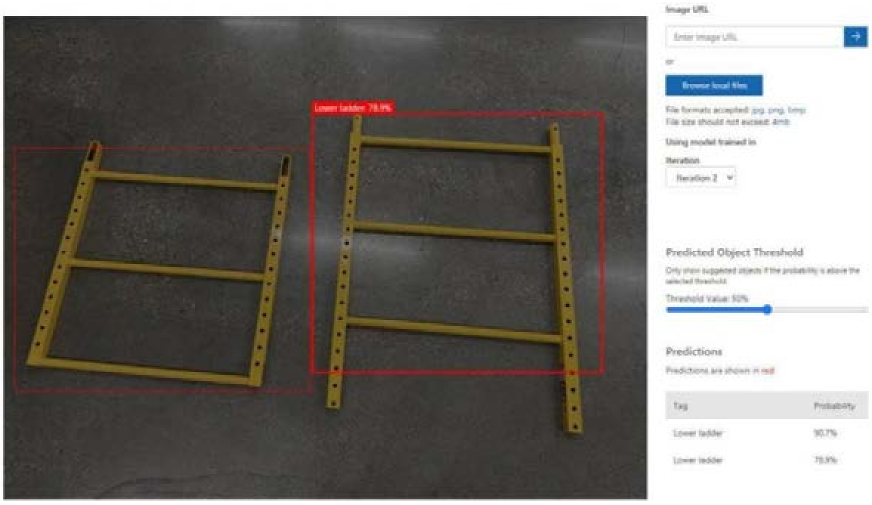


Figure 8 Improvements needed in the model.

6. CONCLUSION AND FUTURE WORK

This research further developed the AR-Driven Task Assistance prototype by integrating object detection function to reduce elemental motions of “Search”, “Select” and “Find” in the Therbligs theory, and designed experiments to verify its direct benefits for construction workers and ease cognitive demanding during performing tasks. By integrating real time object detection into an AR-driven task assistance prototype, it is expected to enhance construction workers’ perception and situational awareness with a wearable, hands-free AR headset, which won’t interfere with workers’ current activities and enable a relatively larger and flexible Field of Vision (FoV) than mobile phone or tablets (Łysakowski et al., 2023).

This research is limited to a single pipeline to realize proposed application scenario, which leaves a researchable question on “Is there an optimal solution for the same function”. Since existing methods do not discriminate well between similar things, it is worth further improving the algorithm or exploring other publicly known algorithms in this domain. Besides, though there are some publications realizing a similar function on HoloLens, it is still worth comparing the performance of different algorithms by using a dataset of the same quality, diversity, and complexity. What’s more, this research is proposed to deploy real-time object detection into an AR-driven task assistance prototype and also verified by scaffolding and miter saw assembly activity, which is aimed at solving practical problems faced by construction industry. However, despite construction industry, other industries might encounter similar issues and challenges awaiting to be further improved. This leaves future efforts to generalize this proposed pathway to other industries and slightly adjust to their specific challenges.

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VISUALIZATION OF WEATHER-AWARE AMBIENT HEAT RISKS WITH GLOBAL ILLUMINATION IN GAME ENGINE

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ABSTRACT: *In recent years, the risk of heat stroke has been increasing due to global warming and other factors, and the Ministry of the Environment has been using the heat index to alert people in urban areas. Still, citizens need help knowing the detailed risk information for their neighborhoods. The heat index considers the human body's heat balance and is measured with specialized instruments, so comprehensive and high-density measurement is difficult. In this research, by using global illumination (GI) and primary weather data obtained from the Open Weather Map API for each area, we can realistically render the sunlight condition considering the weather and map and visualize the heat index per pixel based on shaded CG. Furthermore, by reconstructing urban 3D geometry from Google Maps, we have developed a system that visualizes the ever-changing heat index distribution for an arbitrary location in real time. The system has shown the possibility of reducing the number of heat stroke patients by using this system.*

KEYWORDS: *heat index, WBGT (wet bulb globe temperature), real-time global illumination, game engine*

1. INTRODUCTION

The number of heat stroke cases and deaths continues to increase in modern society due to the effects of severe climate change caused by global warming and the heat island effect (Ministry of Health, Labour and Welfare, 2013~2020).In particular, the proportion of heat stroke patients who suffer heat stroke when outside has reached approximately 60% of all cases (Ministry of Internal Affairs and Communications, 2022), and the possibility that heat stroke is not limited to certain times of the day is also increasing (Ministry of Health, Labour and Welfare, 2018-2022).In addition, the WBGT (Wet Bulb Globe Temperature), an indicator of heat stroke risk provided by the Ministry of the Environment, showed that the value in 2022 exceeded the average value of the previous ten years and that the upward trend is continuing (Ministry of the Environment, 2022). Daily life activities require outdoor maintenance and cleaning work, visits to neighborhood stores, etc., and from the viewpoint of health promotion, visits to parks have become habitual activities for a wide range of age groups (T. Ozaki et al., 2019). The Ministry of the Environment publishes WBGT values for each city on the Web to alert the public (Ministry of the Environment, 2023). However, as one WBGT value is assigned to a metropolitan area, the outdoor environment of each location, comprising different geographical features such as city blocks, parks, and construction sites, is not considered. Facility and site managers must accurately understand the environmental risks visitors and workers face. In addition, schools and other educational institutions are required to regularly measure WBGT before and during outdoor activities such as sports festivals and excursions to ascertain the level of risk so that classes and activities can be conducted more safely (Ministry of the Environment, Ministry of Education, Culture, Sports, Science and Technology, 2021). However, there are limitations to deploying a large number of WBGT measuring devices to collect information. Each individual needs to make decisions and respond based on their own experience. In this study, we propose a new method to visualize the distribution of heat index under sequential changes in the sunshine environment and provide it to general users by using regional meteorological data and 3DCG-based surface solar radiation estimation using global illumination (GI).

2. PREVIOUS WORK

2.1 Okada-Kusaka black-bulb temperature estimation formula

WBGT is an index focusing on the heat balance between the human body and the outside air and is calculated using equation (1), considering the surrounding thermal environment such as humidity, solar radiation, and air temperature. A black-bulb thermometer is required to measure radiant heat, but Okada et al. point out that it is difficult to measure the temperature stably and continuously. Therefore, Okada et al. estimated black-ball temperatures using total solar radiation, wind speed, and dry-ball temperature as explanatory variables (M. Okada et al., 2013). The estimation equation (2) enables the estimation of black-ball temperature from meteorological data on total solar radiation, wind speed, and dry-ball temperature, making it possible to calculate WBGT estimates not only for sunny days but also for a wide variety of weather conditions.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Naotaka Sumida, Taira Ozaki, Satoshi Kubota, Dan Hiroshige, Yoshihiro Yasumuro, *Visualization of Weather-Aware Ambient Heat Risks With Global Illumination in Game Engine,* pp. 133-141, DOI 10.36253/979-12-215-0289-3.13

$$WBGT = 0.7 \times Wet\ Bulb\ Temp. + 0.2 \times Black\ Bulb\ Temp. + 0.1 \times Dry\ Bulb\ Temp. \quad (1)$$

$$Black\ Bulb\ Temp. = \frac{Global\ Solar\ Radiation - 38.5}{0.0217 \times Global\ Solar\ Radiation + 4.35 \times Wind\ Speed + 23.5} + Dry\ Bulb\ Temp. \quad (2)$$

2.2 3DCG-Based Estimation Method of WBGT and Its Application

Yasumuro et al. proposed a method to estimate WBGT by optical calculation using GI for 3DCG rendering to visualize the effect of green shade against heat, as shown in Fig. 1(Y. Yasumuro et al., 2018). First, standard reflectors placed under various shades of green were photographed with a single-lens reflex camera at fixed exposures, and the pixel values were converted to absolute luminance values. On the other hand, the total solar irradiance at the position in the reflector corresponding to each pixel is also measured, and a linear regression analysis is used to determine the correlation between the absolute luminance and the total solar irradiance. WBGT can be estimated from Equation (1) by obtaining the black-bulb temperature using the estimation equation (2) of Okada et al. based on the total solar irradiance calculated using this correlation equation and primary meteorological data such as dry-bulb temperature, wet-bulb temperature, and wind speed, which indicate the conditions at the target location. Furthermore, Yasumuro et al. have made it possible to estimate WBGT without the need for on-site photography by realistically rendering shades using GI with CG that virtually sets the same reflectance characteristics as the standard reflector shown in Fig. 2. By preparing a 3D model of a landmark, it is possible to reproduce solar radiation conditions in 3DCG based on the latitude and longitude of the landmark and its position concerning the sun, making it possible to determine the heat-protection effect of green shade at any given time. In this research, the GI that reproduces photorealistic solar radiation conditions in CG requires a large amount of light path search, and the generation of CG takes time each time the conditions are changed.

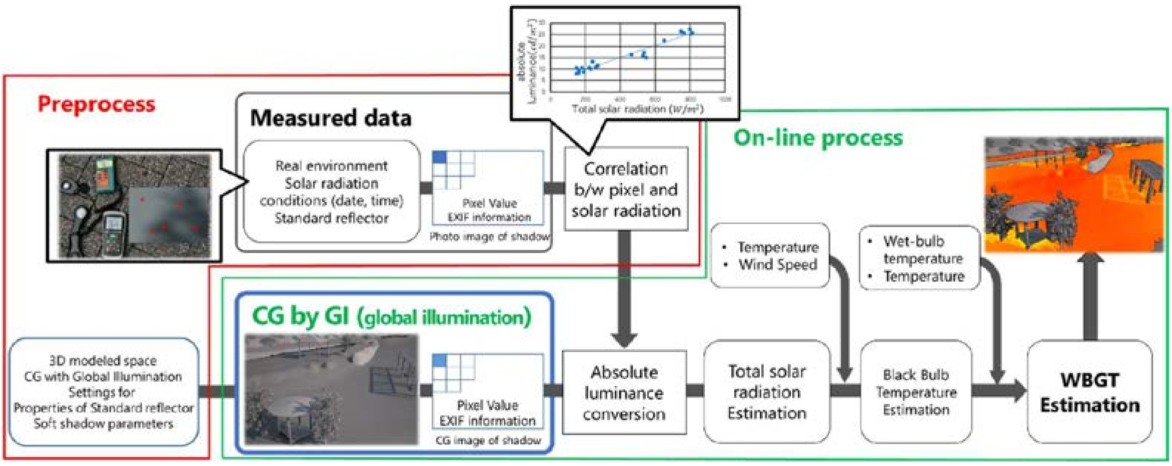

Fig. 1: Process chain for estimation of WBGT and visualization as heatmap image

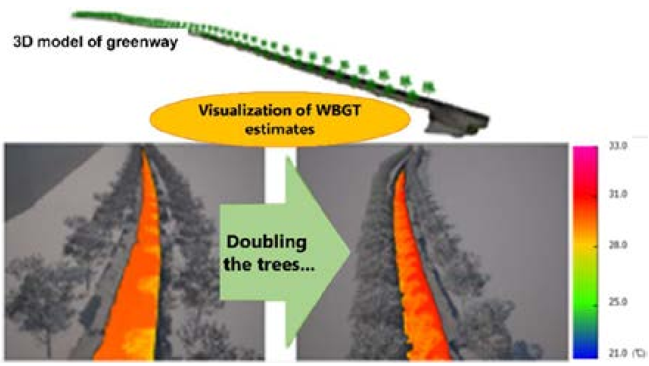

Fig. 2: Example of heat simulation of a greenway with varying plantings
(left: Current planting condition, right: Doubled planting condition)

2.3 Visualization of Environmental Heat Risks with Global Illumination in Game Engine

The authors proposed a method to visualize heat index distribution for ever-changing sunlight conditions regardless of location and stream it to general users on the Web by using a game engine utilizing real-time GI to speed up the generation of solar radiation CG by GI and developing a system to obtain basic weather information in real-time as shown in Fig. 3 and demonstrated the effectiveness of this function (N. Sumida et al., 2022). According to the estimated WBGT value, a function is implemented to visualize the risk of heat stroke as a multi-step heat map using CG by setting colors and interpolation processing using the UV coordinates of the texture based on the colors of the danger levels shown by the Ministry of the Environment in Fig. 4. Although the visualization results are provided universally to the user's terminal via a web browser, this method requires 3D data on the terrain covering the target area for generating CG, and there are many areas where 3D data are not publicly available, limiting the applicable target areas. In addition, the calculation of WBGT requires primary meteorological data for the area. Still, a system that can automatically collect and reference these by region and time needs to be solved. Systematization to solve these problems remains challenging to realize an information service that presents heat risks for any given location and time in response to user requests.

Fig. 3: CG of ground shading with standard diffuse reflection (left) and resultant WBGT heat map (right)

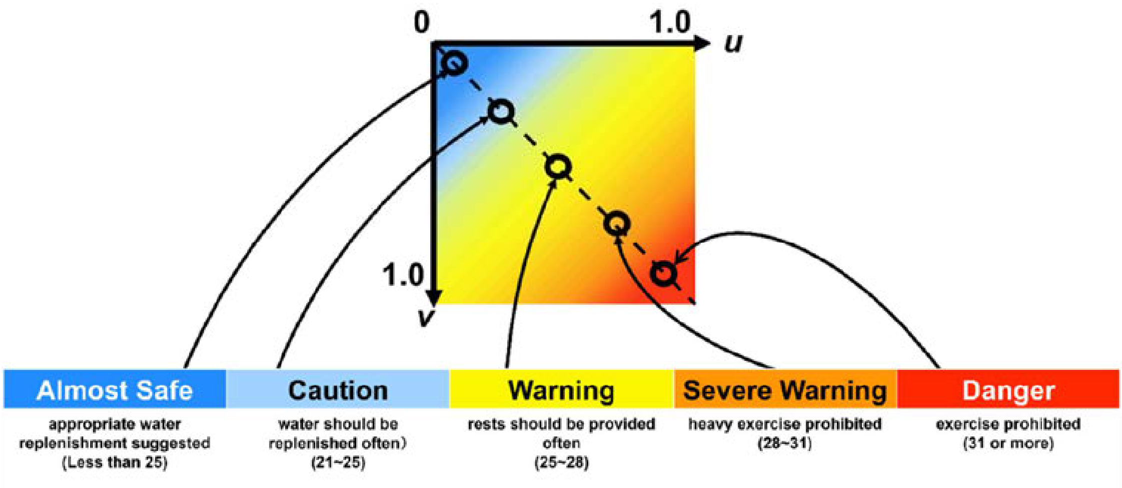

Fig. 4: U-V coordinate of the color texture based on Ministry of the Environment guidelines

3. PROPOSED METHOD

In this study, we propose a system that collects and utilizes necessary data by employing weather data services and 3D information services available on the Internet for an application server with a WBGT estimation function, which the authors have already constructed. Fig. 5 shows the processing procedure of the system proposed in this study. In the real-time GI used by the application server, many image data (called light probes) mapping light source information in all directions are placed in the target space, and information on many light ray paths, including inter-reflection by static objects such as buildings, is pre-calculated as textures. By tracing light probe information, the cost of calculating the synergistic effects of light rays can be significantly reduced, and high-quality computer graphics that include effects such as indirect light can be rendered in real-time. (SILVENNOINEN, A et al., 2017) (K. Kurachi. 2007). Although the target scenes of this study include complex shapes such as trees and buildings, dynamically changing geographic objects are not required, making the system suitable for introducing real-time GI. The user specifies the date, time, and location from a Web browser on the terminal at hand and accesses the application server via the network to use this application. The application server uses the date, time, and location information specified by the user as a query, extracts the corresponding weather data and 3D data from the database, generates CG of the sunshine conditions, and estimates WBGT. The weather data collection server automatically obtains weather information using weather data services provided through public APIs and sensor networks of instruments installed in the region. It stores the relevant information in the weather information database. The 3D data collection server automatically collects 3D data and material information of publicly available geographic objects and stores this information in a 3D model database. For areas where 3D data is not publicly available, a database is created by reconstructing 3D models from map services that can be viewed in 3D on the Internet. By designing the database with the data items required for WBGT calculation in the application server as attributes, data collected from different information sources can be effectively utilized. The 3D data collection server automatically collects 3D data and material information of publicly available geographic features and stores this information in the 3D model database. For areas where 3D data is not publicly available, a database is created by reconstructing 3D models from map services that can be viewed in 3D on the Internet. This system configuration is expected to increase the affinity with the information provided by other services already widely used as information infrastructure and extend the range of applications of this method.

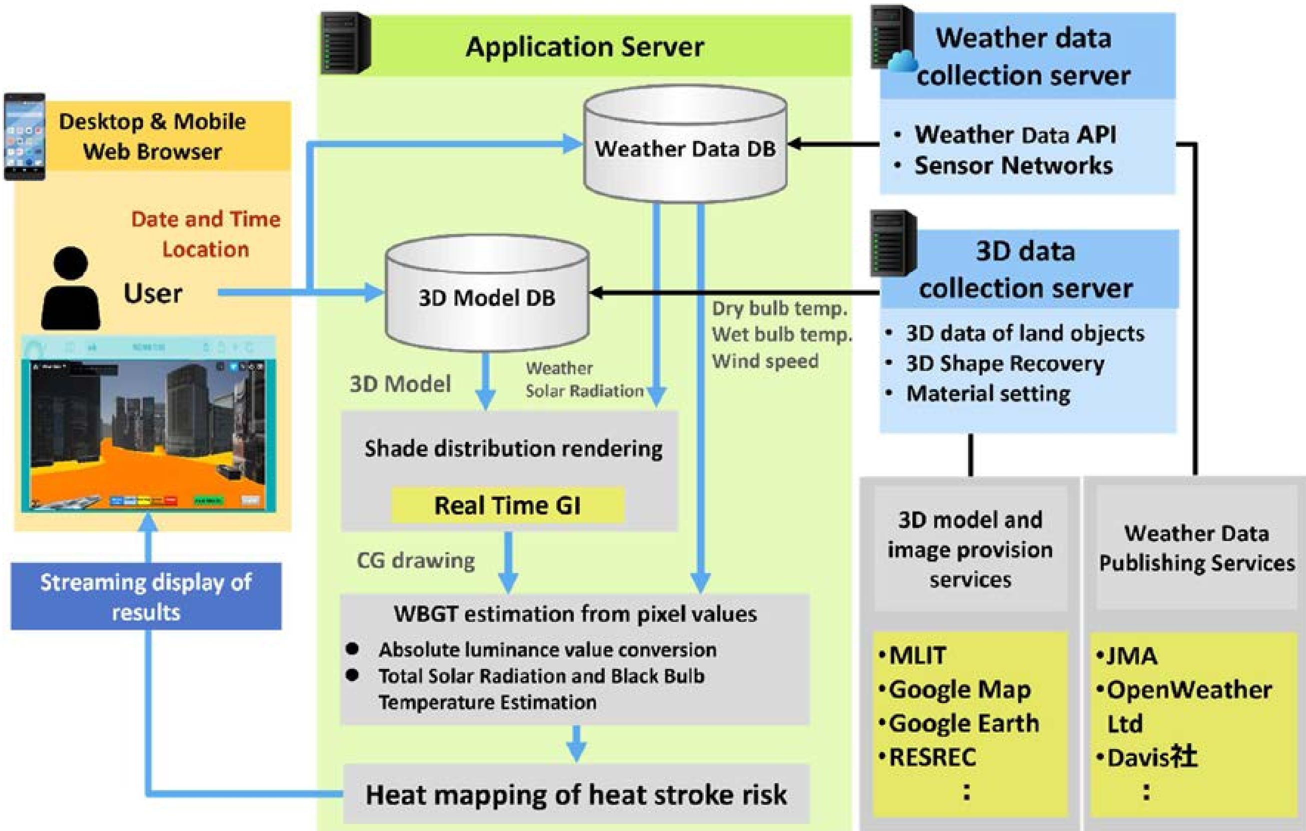

Fig. 5: Proposed System Process Chain

4. IMPLEMENTATION AND VERIFICATION

This study utilized Unreal Engine 4 (UE), a game development platform with real-time GI and sun placement functions based on geographic coordinates and functions equivalent to the exposure settings of a single-lens reflex camera, which can be used to generate realistic computer graphics. An input interface shown in Fig. 7 is implemented in the UE to allow users to select specific locations. After entering a place name, a button for selecting the corresponding place name is displayed. When the user clicks the button, the user is automatically redirected to a map showing 3D data of the corresponding area. When the user clicks on a button, the user is automatically redirected to a map displaying 3D data of the corresponding area. When the place name is searched by prefecture, all buttons for the corresponding city, town, or ward are listed and can be selected in a scrolling format. The method of setting the date and time and the output process of the heat map of WBGT distribution after setting the date and time are based on the authors' existing method.

The weather data collection server in the proposed system uses Open Weather Map API provided by Open Weather to obtain publicly available weather forecast data. Open Weather Map API is suitable for this study because it can provide basic weather information required for WBGT estimation, as well as information on specific locations and times required for CG generation using real-time GI. In addition, a DAVIS VantagePro2 sensor is used to collect real-time weather information at individual sites. The Open Weather Map API and the VantagePro2 are suitable for this study because they are commercially available and can be installed at individual sites. Considering that VantagePro2 sends data in Json format to the weather data collection server, as shown in Fig. 7, we implemented a parsing function in the application server UE to analyze the received Json data and sort them into attributes suitable for this system. This implementation makes it possible to comprehensively process the acquired information and convert it into a format suitable for the proposed system, even when the data sources differ.

Fig. 6: Pull-down menu interface for selecting location incorporated in the game engine

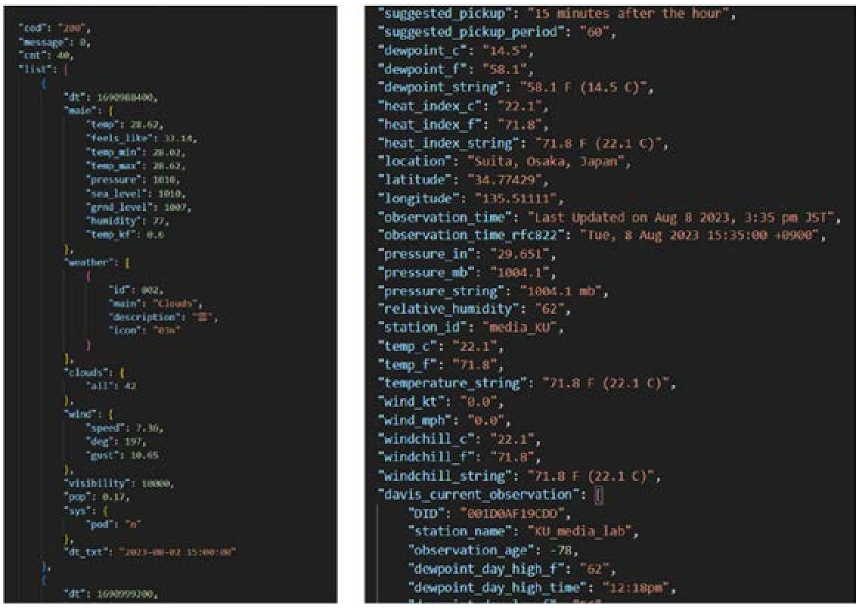

Fig. 7: Json data from Open Weather Map API (left)
and Json data from VantagePro2 (right)

The authors implemented a system that enables data acquired by a weather data collection server to be stored in a weather data database created in the relational database service (RDS) of AWS, a cloud service provided by Amazon, Inc. In addition to the basic meteorological information necessary for WBGT estimation, the database is designed to prevent data inconsistencies by setting latitude/longitude and place name information necessary for location identification as attributes. However, although wet-bulb temperature is required to calculate WBGT from Equation (1), some measurement equipment measures humidity instead of wet-bulb temperature. Open Weather Map API and VantagePro2 used in this paper do not measure wet-bulb temperature, so they calculate an approximation of wet-bulb temperature from humidity and dry-bulb temperature. If the equipment measures wet-bulb temperature, it is directly stored in the database, and if it cannot measure wet-bulb temperature, the system calculates an approximate value.

The 3D data collection server in the proposed system acquires extensive and detailed 3D city data publicly available, such as PLATEAU provided by the Ministry of Land, Infrastructure, Transport and Tourism in Japan. As a method of storing the acquired 3D data, we are considering a method for directly storing the data in a database or storing the 3D data in a cloud service such as Dropbox or Google Cloud Platform (GCP) and storing only a link to the destination in the database. In cases where open-source data is unavailable, we adopt a method of reconstructing 3D data from information sources such as 3D data from online map services such as Google Maps. The verification procedure is to set multiple waypoints in Google Maps, as shown in Fig. 8 (left), and create a KML file that contains geographic coordinate information to specify the route of the viewing viewpoint. By importing and executing the created KML file into Google Earth, it is possible to capture virtual aerial images that simulate UAV flight as shown in Fig. 8 (right), and through 3D reconstruction by SfM using photogrammetry, 3D data acquisition, as shown in Fig. 9, is realized. With the above implementation, obtaining the data necessary to generate a heat map is now possible using only the specific date, time, and location information entered by the user.

Fig. 8: Waypoints specified by our KML file depicted on Google Maps (Osaka: Suita, Japan) (left) and the captured virtual aerial photos through the waypoints in Google Earth (right)

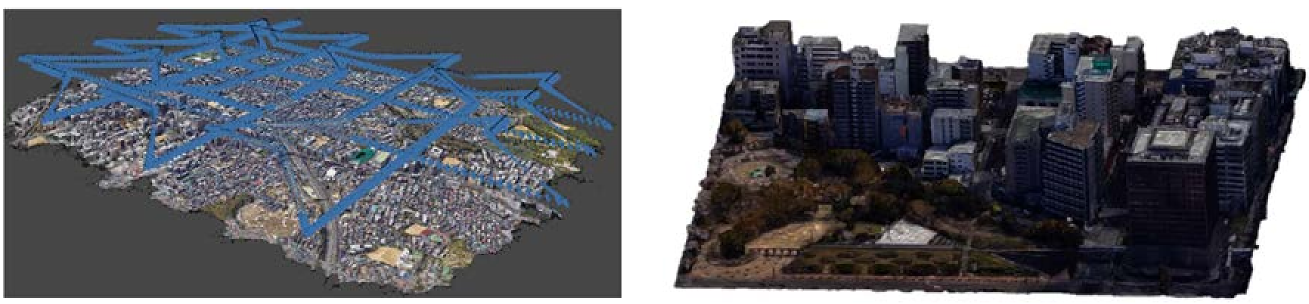

Fig. 9: 3D reconstruction based on SfM using the photo images in Fig. 8 (Osaka: Suita City, excerpts, Japan)

5. EXPERIMENTAL APPLICATIONS

5.1 Case Study in Shibuya and Shinjuku City, Tokyo

The following is an example of applying the proposed system to 3D data of Shibuya and Shinjuku city obtained from PLATEAU, a 3D data utilization service provided by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). Furthermore, we show that the system can visualize the detailed distribution of heat stroke risk during the day and night by combining the system with time-dependent weather data stored in the weather information database, as shown in Fig. 10 and Fig. 11. At the time of writing this paper, the weather information for August 2023 was not available, so the data for August 11, 2022, was used for CG generation.

5.2 Examples of heat stroke risk prediction validation

During the Golden Week (early-May holiday season in Japan) of 2023, temperatures exceeding the average of 18.8°C announced by the Japan Meteorological Agency were observed. The maximum temperature in Tokyo on May 6 reached 27.9°C, which potentially increased the risk of heat stroke for people outside the city. This result shows that the risk of heat stroke in front of Shinjuku Station was at a level where it is recommended to actively hydrate oneself (Fig. 12). This result suggests that even during periods when the risk of heat stroke is generally recognized as low, the risk may still exist, and this system is an effective means of verifying this.

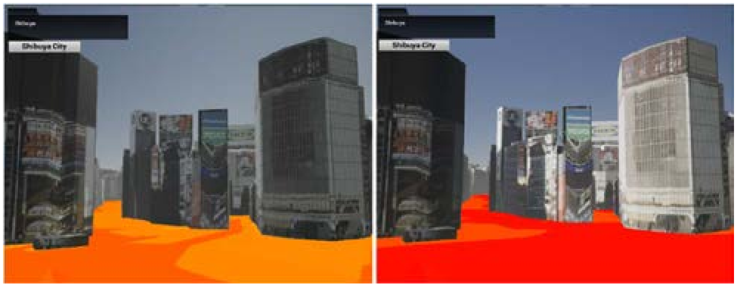

Fig. 10: Heat map of Shibuya City during the daytime
August 11, 2022, at 10:00 (left) August 11, 2022, at 14:00 (right)

Fig. 11 Heat map of Shinjuku City at night
August 11, 2022, at 18:00 (left) August 11, 2022, at 22:00 (right)

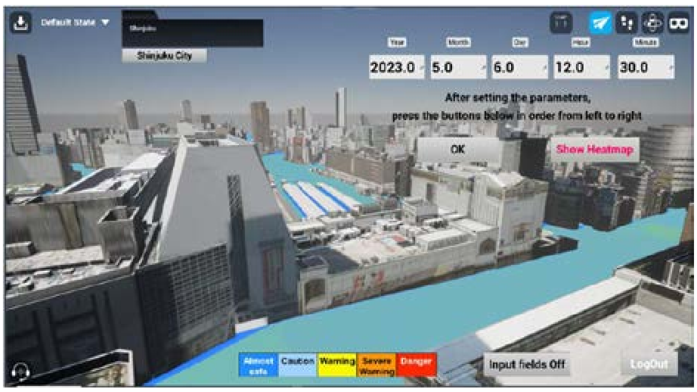

Fig. 12: Heat map of Shinjuku City during the day May 6, 2023, 12:30 p.m.

5.3 Case Study in Suita City, Osaka

For areas where open-source 3D data such as PLATEAU (see (1)) is not available, this method can be applied to 3D reconstruction using SfM from existing services such as Google Map's 3D view to generate a heat map as shown in Fig. 13. By importing kml files containing geographic coordinate information into Google Earth, it is possible to take aerial images that simulate UAV flights. We have shown that large-scale collection of 3D data is possible at low cost by using Google Earth to take comprehensive aerial photographs of surrounding areas.

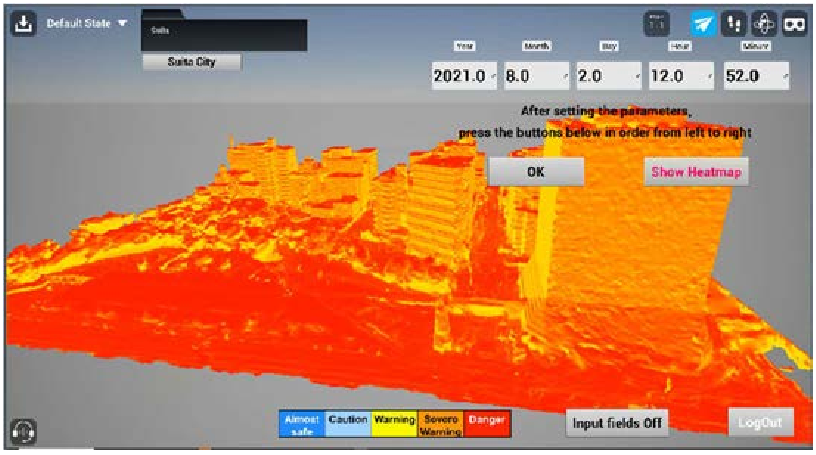

Fig. 13: Suita City: Heat Map
(3D reconstruction based on SfM), August 2, 2021, 12:52 PM

6. CONCLUSION

In our research, we developed a system that utilizes public weather information and 3D data using a game engine, enabling WBGT estimation and real-time heat maps for various regions and times. In the future, we aim to create a new solar radiation correlation equation that enables WBGT estimation on cloudy days based on weather information such as clear and cloudy skies obtained from meteorological data. In addition, the physical characteristics of 3D models of geological objects have yet to be considered. We plan to analyze the impact on WBGT by the reflectance and transmittance of surrounding buildings' surface materials and vegetation, considering the findings of prior CFD (computational fluids dynamics) studies. Incorporating the results of these analyses into the model will allow for a more accurate and realistic assessment of the thermal environment.

ACKNOWLEDGEMENT

This work was partially supported by the Collaboration Research Program of IDEAS, Chubu University IDEAS202321 and Organization for Research and Development of Innovative Science and Technology (ORDIST) in Kansai university.

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IMPROVING SENSE-MAKING FOR CONSTRUCTION PLANNING TASKS USING VISUAL AND HAPTIC STIMULI IN VIRTUAL REALITY ENVIRONMENTS

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ABSTRACT: *Design documents, drawings, and specifications are visual representations that are fundamental and prevalent in today's construction engineering practice. Construction specialties (e.g., structural, mechanical) rely on these visual representations to express and draw meaning during collaborations. Construction engineering and management (CEM) students must acquire the knowledge, skills, and abilities — a key example of which is perceptual competence —for interpreting visual representations to facilitate efficient task execution, such as planning. Empowering learners with new technology using robust real-world immersion and interactive features is a significant step towards this target. The presented research explores new human-machine interactions to determine the best way for CEM students to learn through the combined senses of sight and touch. The approach merges visual and haptic interactions within an immersive environment to enhance perception and reasoning skills. The research demonstrates how CEM learners interact with and interpret the meanings of information within a planning task. It explores how VR and haptic technology augment the ability to recognize meanings — a new type of representational competency — for improved interpretation of information related to components with respect to engineering disciplines and sub-systems in a CEM, and investigates learners' problem-solving ability by using perception-rich enhanced virtual reality (VR) and haptic affordances.*

KEYWORDS: *haptic cues, human-computer-interaction, design interpretations*

1. INTRODUCTION

To satisfy the educational needs of STEM learners and foster essential 21st-century skills, such as critical thinking, reasoning, problem-solving, collaboration, and communication, educators must integrate innovative technology into the learning process (NSF, 2020). To address these requirements, human-computer interaction (HCI) offers viable solutions to augment human senses and enrich sensory input, including vision, hearing, smell, and touch (Manchanda et al., 2017).

The sense of touch or haptics is one of the most informative human senses. This sense includes both cutaneous and kinesthetic sensations. Embracing haptics opens up new possibilities to expand human capabilities, such as improving manual dexterity and enhancing sensory perception (Chryssa & Julie-Ann, 2020). This research takes advantage of the HCI affordances and explores the use of haptic technology in learning for Construction Engineering and Management (CEM) students.

Fundamentally, to explore the use of haptics in CEM learning, the presented approach draws on an individual's spatial-temporal cognitive ability (STCA) (Mutis, 2018a). Spatial-temporal ability allows learners to effectively manage and comprehend significant amounts of spatial (how design components are related to one another in the 3D space) and temporal (the logic in a process, such as the order, sequences, and hierarchies of the resources within a construction task) information (Mutis, 2018a). Limited or no ability to process spatial and temporal information (i.e., lack of spatial and temporal cognitive ability hinders the understanding of designs and management of the varying local conditions (e.g., unplanned conditions) (P. Antonenko & I. Mutis, 2017; P. D. Antonenko & I. Mutis, 2017; Mutis, 2014, 2015; Mutis, 2018b). The ability helps learners to conceptualize three-dimensional relationships between objects in space and mentally manipulate them as sequential transformations over time.

The STCA cognitive ability allows the CEM learners to recognize meanings and facilitates coupling observed representation to the given contexts – a new representational competency. The coupling abilities (spatial and temporal) significantly benefit the decision-making process. Individual spatial-temporal abilities are associated with high cognitive reasoning that defines the cognitive-processing chain — from basic visual attention to higher-level reasoning, such as an interaction between organizing, performing, and supervising the effectiveness of a plan (Mutis, 2018a). For instance, planning is a highly cognitively demanding task where STCA plays a pivotal role. Planning is critical as the learner couples observed representation in a given context to organize, perform, and supervise the effectiveness of a plan while interpreting information from engineering designs. Effective STCA training enables individuals to instantly identify concepts, events, and patterns for comprehension and projection,

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Ivan Mutis, Marina Oberemok, Nishanth Purushotham, *Improving Sense-Making for Construction Planning Tasks Using Visual and Haptic Stimuli in Virtual Reality Environments,* pp. 142-154, DOI 10.36253/979-12-215-0289-3.14

streamlining actions, solutions, and implementations in planning.

The presented approach explores the uses of haptic technology to augment cognitive capabilities, in particular the STCA. The STCA augmentation effect is from the cognitive load reduction by using a new sensing channel (haptics) in the cognitive process by liberating mental resources for other cognitive tasks (Sweller, 1988; Sweller et al., 2019), potentially enhancing spatial and temporal processes that are fundamental in problem-solving tasks. The assumption is that learners can rely on their haptic sense to reduce efforts of converting cognitive processes into physical actions— alleviating the burden of effort for processing spatial (e.g., spatial configurations of design components in the 3D space) and temporal (e.g., the logical sequence of design components for their assembly) information. The use of new senses (haptics) is a form of increasing the impact of embodied intervention in the cognitive process by, for instance, facilitating tracking information and gaining object rotations to feel and comprehend spatial relations more accurately (Tran et al., 2017).

By using perception-rich enhanced virtual reality (VR) with haptic affordances, this study addresses the following questions:

1. What aspects of haptic stimulus impact the learners' development of representational competence for better interpretation of information related to designs in a CEM? The research outlines the importance of improving *spatial-temporal skills* to facilitate high-level reasoning in complex situations.
2. What *new HCI factors*, combining visual and haptic (VH) interactions with engineering designs, enrich the perception and reasoning skills of CEM learners, leading to more accurate and efficient task execution? The solution presents *a haptic language* that implies tactile cues enhancing spatial awareness for the given context.

2. BACKGROUND

Researchers in STEM education are exploring the ways in which haptic technology can enhance the learning process, including improving student engagement, conceptual understanding, and skill acquisition. Early studies focused on developing haptic devices for enhancing spatial awareness and visualization skills (Liu et al., 2003; Williams Ii et al., 2001). Later research underlined the benefits of haptic feedback in improving interactions and spatial guidance (Jong, 2014; Takahashi et al., 2009). As demonstrated in further publications, augmenting VR with haptics increases overall task performance and the users' perceived sense of presence (Cooper et al., 2018; Kreimeier et al., 2019).

Over the years, haptic interventions in architecture, engineering, and construction (AEC) have been applied to simulate assembly tasks (Medellín-Castillo et al., 2015) and develop vocational training for construction personnel such as carpenters, plumbers, and masons (Jose et al., 2016; Ranjith et al., 2014). Current research aims to cultivate more sophisticated haptic devices and techniques for human-machine interaction in AEC, including haptic feedback for mixed reality and teleoperation (Adami et al., 2022).

In general, haptics is extensively used in engineering learning, including training, physics and chemistry simulations, robotics, and automation (Prabhakaran et al., 2022; Sanfilippo et al., 2022). Engineering education utilizes haptic interfaces to provide students with hands-on experience with virtual simulations. Likewise, vocational training with haptics provides realistic practice in handling heavy machinery and tools. Lastly, by using haptic devices on remote-controlled construction robots, operators are able to discern the properties of various objects and materials during the manipulation (Alakhawand et al., 2022). Thus, haptic technology shows promise to transform traditional learning and training methods, offering advantages such as enhanced knowledge retention, engagement, skill acquisition, safety, and accessibility (Mastrolembo Ventura et al., 2022).

Several studies have been conducted on assembly techniques, but only a few have explored the incorporation of haptics due to their relative novelty as an assistive tool in STEM learning. However, the development of haptics shows potential for enabling innovative approaches to enhance cognitive and motor skills, particularly in tasks like modeling, assembling, and teleoperation. For virtual assemblies, Yuan et al. (2008) introduced an augmented reality (AR) approach, utilizing a virtual interactive tool called VirIP and a visual assembly tree structure (VATS). This system enables assembly operators to seamlessly follow a pre-defined assembly plan/sequence without requiring sensor schemes or markers on the assembly components. Hu and Zhang (2012) presented a method leveraging a 3D game engine and software component technique to rapidly construct a reusable component library to develop virtual assembly experiments. In recent work, Li et al. (2020) proposed a framework with advanced computations such as runtime degrees of freedom (DOF) determination, disassembly directionality computation, and assembly/disassembly sequence generation. These computations efficiently integrate assembly constraint information into a virtual assembly application with minimal effort required.

Haptic technology allows the transfer of touch-based information between humans and computer interfaces (OED, 2020). Haptics can enhance the learning experience and support an environment that cultivates student engagement, motivation, and interest in the subject matter (Tytler, 2020). Haptic interaction is crucial for a sense of presence and manipulating objects in remote or virtual environments with manual dexterity (Kortum, 2008, p. 25). For example, by providing users with tactile cues, haptics makes the digital environment more interactive and informative.

In the AEC discipline, there are proposed haptic interventions that aim to assist users in accomplishing an engineering task providing guidance for the decision-making process. Rahimian and Ibrahim (2011) proposed a haptic-based VR 3D sketching interface to improve novice designers' engagement with "problem-space" and "solution-space", leading to increased artifact maturity in collaborative conceptual architectural design. Following Christiand and Yoon (2011) work, haptic-path sequence guidance reduces the assembly time and the travel distance that enhances the working performance of virtual assembly tasks. Also, the availability of haptics in large immersive environments can contribute to future advances in virtual assembly planning and factory simulation (Pavlik et al., 2013). Yeh et al. (2013) suggested that multi-symbolic representations (text, digits, and colors) in haptics-enhanced virtual reality systems have the potential to help collaborative work effectively. James et al. (2019) proposed a bi-manual haptic interface for skill acquisition in surface mount device soldering. Coffey and Pierson (2022) demonstrated the effectiveness of the proposed haptic guidance system for co-navigation of non-holonomic vehicles through teleoperation. Williams et al. (2023) presented a framework for active haptic guidance in mixed reality using one or more robotic haptic proxies to influence user behavior and deliver a safer and more immersive virtual experience.

The primary focus of the mentioned studies was to improve the understanding of a process for training (e.g., the process of assembling building components). The studies have incorporated haptic guidance into the assembly processes, which helped users receive tactile feedback during the assembly tasks. However, the haptic guidance implementations fell short in providing spatial awareness and addressing high-order cognition in cognitively demanding tasks such as identification of the dependencies or hierarchy of building components for planning. While the haptic guidance aids in recognizing information about movements in training tasks through haptic feedback, the approaches do not offer a comprehensive understanding of the entire spatial context or interconnections between various building components. The presented study aims to overcome these limitations by exploring spatial-temporal cognitive abilities using visual and haptic stimuli.

Haptic feedback

Using electronic devices, we encounter multiple interactions, including sounds, flashes, and buzzing haptics (Müller, 2020). Such a combination of sensory stimuli allows the user to be fully engaged in the experience, which enriches the overall quality of the interaction. A crucial aspect of this set is haptic feedback, which draws from the psychological nature of interaction with the environment and other humans (e.g., social touch). Therefore, achieving precise replication of haptic signals in devices requires a deep comprehension of how humans perceive and attribute meaning to tactile interactions to portray their semantics accurately.

The human skin's discriminative ability arises from a dense network of cutaneous receptors allowing us to differentiate fine touch, pressure, texture, and temperature (Fulkerson, 2020). This adaptability of touch perception, known as adaptation rate, enables us to prioritize novel sensations while filtering out constant stimuli. Unlike some other senses perceived passively, haptic perception is inherently interactive and bidirectional – we actively explore and manipulate the environment to extract tactile details.

To recreate physical sensations, HCI incorporates various types of haptic technology, including force, vibrotactile, ultrasonic, thermal, and other forms of haptic feedback (Hatzfeld et al., 2015). Haptic interfaces allow users to experience tactile sensations while manipulating objects, discriminating textures, and applying forces in the virtual and physical environment.

According to the literature (Adilkhanov et al., 2022), haptics performs three primary functions such as simulation, teleoperation, and guidance. Through *simulations,* haptic feedback imitates physical interaction with the environment and its attributes to heighten the realism of learning scenarios. In *teleoperation,* the haptic interface provides a two-way communication channel between a robot and an operator, allowing the operator to perceive tactile feedback from the robotic tool (Luo et al., 2019). As part of the *guidance* process, haptics implement tactile patterns to derive directional cues to the user (Huang et al., 2019).

Guiding haptics becomes especially beneficial for facilitating the decision-making process and fostering problem-solving abilities by providing tactile cues to assist users in performing tasks or enhancing interactions in a physical and virtual environment (Bluteau et al., 2008; Feygin et al., 2002). This haptic function utilizes touch-based sensations to provide the users with real-time information, helping them make informed decisions and improving their overall performance and understanding of the context. Research suggests that using intuitive haptic guidance to assist the movement reduces errors (Mugge et al., 2016). Moreover, a partial-then-full haptic guidance strategy seems the most effective in improving learning outcomes (Teranishi et al., 2018). The most common applications of guiding haptics include vibrotactile feedback, often incorporated into commercial smartwatches for haptic notifications and alerts.

Haptic guidance can be achieved through a *haptic code* that utilizes touch-based symbols (e.g., haptic icons or "hapticons" (Enriquez & MacLean, 2003)) to instantly deliver information to the user via vibrations, pressure, or movement (Hatzfeld et al., 2015, p. 75). According to Enriquez et al. (2006), haptic code has to meet the following conditions in order to offer explicit meaning:

- *Differentiable*: All haptics must be distinct from one another when presented either alone or in any common haptic combinations.
- *Identifiable*: Once a meaning has been connected to a stimulus to form an icon, it must be simple to recall.
- *Learnable*: The associations between meanings and stimuli should be intuitive and easily remembered.

The elementary functions of the haptic code include providing notifications with neutral feedback and signals with either positive or negative meaning in response to the user's actions.

Haptic code can be applied even on a broader spectrum, e.g., for rendering abstract models or concepts as a new modality for communication. At the lowest level, haptic devices notify users of an event, their identity, or their current state or contents. A higher level of abstraction implies haptic associations that allow the users to identify interdependencies and determine a sequence of actions by assigning physical sensations to an object hierarchy. Accordingly, systematic, perceptually guided haptic design can support expressive and nuanced communication that qualifies as a new haptic language.

3. METHODOLOGY AND APPROACH

The study consists of two main phases: (1) the creation of the experimental training platform, designed to be interactive and informative; (2) experimentation, with active student participation for practical application and assessment of the learning outcomes. This comprehensive approach provides an effective and engaging program for students to develop their skills and comprehend complex building concepts in a virtual and immersive environment. The presented research is the first phase, including a case example to illustrate the approach.

Immersive virtual platform

The VR design consists of the development of a VR environment based on the detailed design of a building project (e.g., a small residential building). See Fig 1. The design was represented in a Building Information Model (BIM) with at least a Level of Detail 300. The BIM model contains rich data on engineering systems through represented objects or component assemblies, such as quantity, size, shape, location, and orientation. The design was exported as an Industry Foundation Class (IFC) file to preserve the semantic information of the building components. The exported model was then imported into Unity for two purposes. First, it acts as a reference point in the form of a translucent building, allowing the user to place building components accurately. Second, it is semantically broken down into corresponding building components to build game objects. The resulting structures were game objects created based on the standard categorization of the building into Sub-Structure and Superstructure and further classified into Structural, Architectural, and Mechanical components.

It is critical to note that the created game objects were set for true building scale, generating an immersion that represents dimensions for easy manipulation in the VR environment. Each game object had a representation that described data and text information in a structured format, involving attributes as game elements based on IFC structure. For example, each object game had data related to the activity (used for planning) in their element attributes (element descriptors). The element attributes held in addition to the planning activity information associated with unique haptic feedback, as discussed in the section below. For a logical representation in planning, game objects were nested based on a work breakdown structure (WBS)— a hierarchical tree structure subdividing the deliverables and work. The WBS disciplines will deliver the work specified in each work package—the lowest level in the WBS that represents a specific amount of work. The work package as product and deliverable has a VR object representation. The structure of these components is shown in Fig. 1.

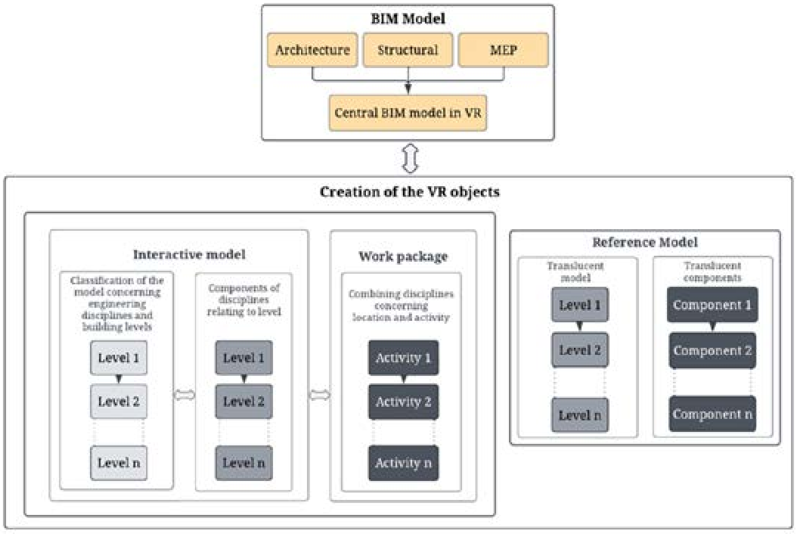


Fig. 1: Design structure of the VR platform.

Experimental Platform

Unity software integrated with a VR headset Oculus Pro and a full set of haptics devices (see 2) were used for the development. This state-of-the-art platform provides users with a fully immersive experience. An example of the visualizations is shown in Fig. 5a and Fig. 5b. They illustrate a dashboard and virtual design components where users learn virtual manipulation, featuring an informative activity pane to hold building components as activity tiles and servicing as a comprehensive reference model for planning activities to enhance the overall learning experience.

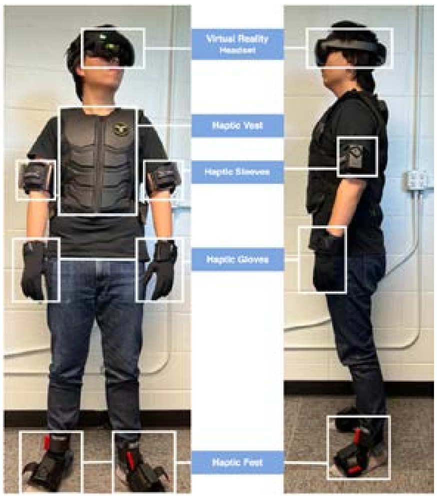


Fig. 2: Haptic devices for the VR platform.

Haptic (*vibrotactile*) code

The researchers systematically structured the haptic code as feedback for the simulation and experimentation in VR environment. The code contains the logical patterns that guide the user's manipulation of the building components through interaction augmented by haptic feedback. The code has signatures expressed as haptic icons, i.e., a haptic icon is a brief haptic stimulus associated with meanings. The haptic icons were designed to intuitively comprehend cues about a function of the object and interact (user-object effects) in the virtual environment. The code is a form of primary language wherein each icon is a constant pattern with associated semantics. The learners (users) are required to get familiarized with the code (akin to learning a primary language to operate a system) *a-priory*.

To associate semantics to the haptic code, four key perceiving haptic features play a crucial role in defining the tactile experience:

- *Intensity*. It governs the strength or magnitude of the tactile sensation delivered to the user. It determines how strong or weak the haptic feedback feels, allowing for the creation of subtle or intense tactile perceptions.
- *Sharpness*. It relates to the perceived abruptness or distinctness of the haptic sensation. It influences whether the sensation feels smooth or sudden.
- *Duration*. It refers to the length of time of the perception of haptic feedback. Short durations can convey quick events, while longer durations can simulate prolonged interactions or sustained sensations.
- *Granularity.* It is determined by the frequency of impulses and their spacing. The more granularity, the more rapid the impulses.

Manipulations with these haptic features enable prototyping and fine-tuning haptic experiences to match specific interactions and simulation scenarios, enhancing user engagement and immersion in virtual environments. The combinations of the haptic features assigned to a haptic device evolve into distinctive haptic patterns.

Haptic code (*vibrotactile*) types

The haptic code consists of two types of haptic feedback: operational and functional.

Operational

It refers to haptic feedback of the basic human-computer interaction (HCI) with the elements of the virtual environment, such as feedback on actions on the system components (to select, cancel, move, etc.). The approach includes three types of operational haptic feedback:

- *Positive* to reflect the correct actions of the user by giving soft impulses with low or medium intensity;
- *Negative* to associate the mistakes and has more even rigid impulses, medium or high intensity;
- *Neutral* to provide alerts to the user regarding updates or notifications (it is presented as a row of short impulses with gaps in between).

Functional

It refers to the feedback that gives semantics associated with activity planned in VR deployment.

Parameters of duration (D), granularity (G), intensity (I), and sharpness (S) define the functional haptic code. The combination of parameters defines features that indicate semantics. The combination can be represented in a two-dimensional matrix of *n* rows (where *n* is the number of combinations). See Fig. 3. Each row represents the distribution of values of parameters (D, G, I, S).

A VR object will have an associated haptic code combination (DGIS), representing a specific value and semantics.

Fig. 1 illustrates the approach conceptualization of the intersecting components (virtual environment, structure of VR objects, haptic (vibrotactile) code, semantics haptic feedback (as semantics), and the spatial temporal cognitive ability (while interacting with problem solving in CEM). The arrangement impacts the spatial-temporal cognitive abilities of learners, assisting them in accurately defining the sequence of activities through the integration of visual and tactile cues.

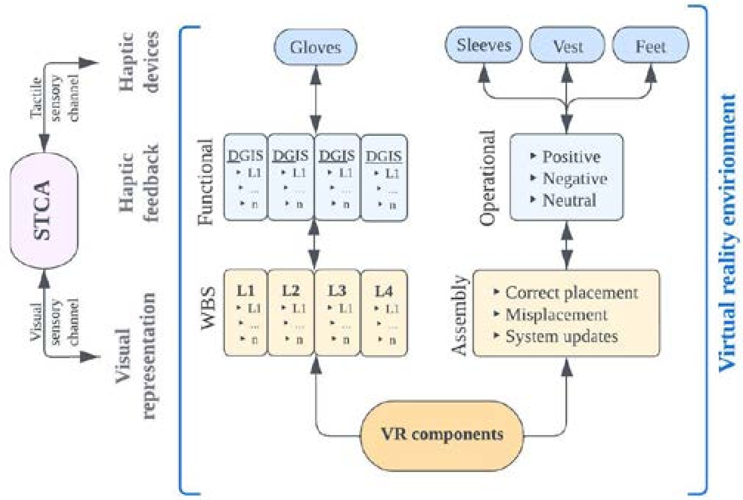


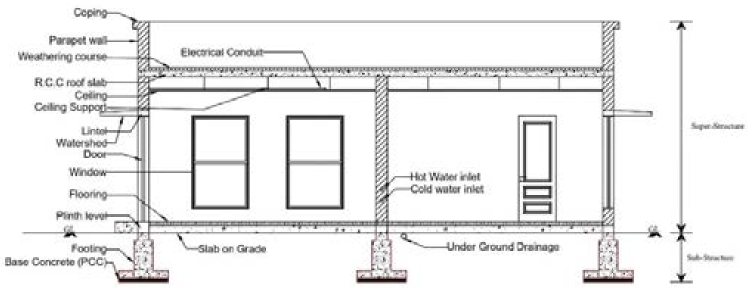
Fig. 1: Approach conceptualization.

Case Example

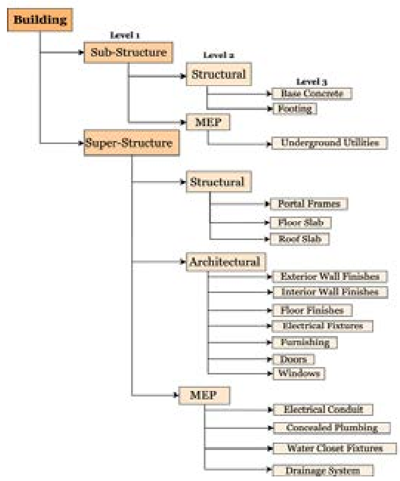
Learners are required to plan the construction of a small building design section in the VR environment (see Fig. 2). The user should build the plan by identifying construction work packets (associated components and activities). A work package (construction product deliverable) serves to establish a coherent and feasible subdivision of tasks within the construction project. Each packet has associations with physical areas (work zones) to cover all the components of the design.

A work breakdown structure (WBS) that incorporates the components and activities associated with the small building design (see Fig. 2a) is presented as a dashboard in the VR environment (see Fig. 5a). The WBS is used as a baseline for planning. The first milestone is set for substructure completion of the building design, and the second is set for the superstructure (see Fig. 2b). Each building component from the design is the deliverable of an activity.

The assembly sequence for each activity and packet (construction product deliverable) is based on the Finish-To-Start (FS) inference (logical relationship between two activities). A finish-to-start relationship implies that the predecessor activity needs to be finished before any subsequent actions can start.



(a) Building components



(b) A breakdown of the building components in a hierarchical structure

Fig. 2: Construction product deliverables from work breakdown structure (WBS).

After the user selects the packet from the dashboard in the virtual environment (see Fig. 5a), the next step is to select, drag, and drop the design component (deliverable) of the small building on a virtual layout by performing a virtual walkthrough (see Fig. 5b).

(a) A dashboard servicing as a reference model to visualize WBS packages for conceptual planning.

(b) Snapshot of the mapping between the work package and the reference model (virtual layout of the building).

Fig. 5: Interactive haptic activity for a planning task in the VR environment.

The order of activities corresponds to the deliverable sequence, and each deliverable has an associated location in the virtual layout. The assumption for the case example is that the presented activities depend on the completion of others before they can begin (FS precedence). Planning these activities takes the dependencies (precedents) into account by arranging activities in a logical sequence. The arrangement of all deliverables is the planning of the construction section of a small building design in the VR environment.

The users need to locate (by dragging and dropping) all the deliverables of the building section in the virtual layout space during the virtual walkthrough. By completing all the packets in the dashboard, the user can complete the planning of the building.

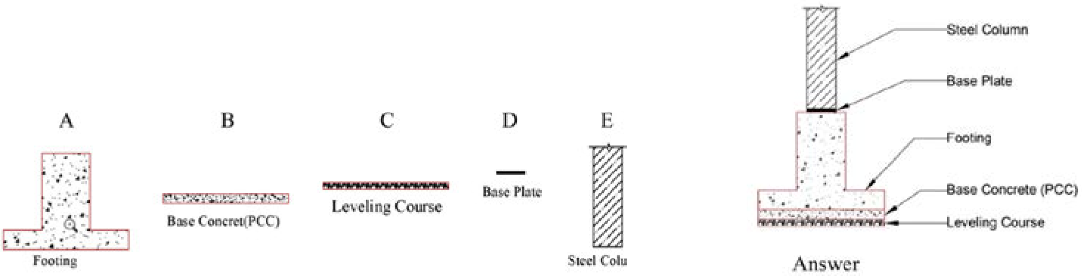
Haptic feedback is an interactive feature that responds to the actions of the users within the VR environment — i.e., certain actions generate a type of haptic feedback with associated code (meaning). When the user drags and drops a deliverable on its selected location, there are two potential haptic feedback: functional and operational. Thus, *operational* and *functional* haptics complement each other to assist with the understanding of the semantics and ensure proper placement of the system components. Operational haptic feedback is on basic human-technology interaction, while functional haptics are systematically organized and tailored to specific semantics that indicate hierarchical structures.

For example, if the deliverable is placed correctly, operational haptic feedback (*positive operational feedback* using soft impulses with low or medium intensity) would indicate a code that will inform the user that the correct location was correctly selected. However, if it is misplaced, operational feedback with the associated code (*negative operational feedback* using rigid impulses, medium and high intensity) is given to indicate to the user the error of displacement. Another example of operational feedback is *positive* when the user reaches a designated milestone while finalizing the packets from the WBS. Otherwise, *negative* feedback is given — indicating that more selections are required for planning. *Operational* haptic (vibrotactile) is produced by the haptic sleeves, which offer feedback for component manipulations like selection and canceling, as well as the haptic vest and feet, which are responsible for delivering notifications, success signals, and failure alerts. Code examples of operational feedback are shown in Table 1.

Table 1: Operational haptic feedback code

Events	Meaning	Haptic feedback	Intensity		Duration [ms]	
Select	A component is taken	Medium intensity, medium sharpness, and short duration, two short impulses with increasing intensity	low	0.2	short	150
			medium	0.5	short	200
Cancel	A component is thrown	Medium intensity, medium sharpness, and short duration, two short impulses with decreasing intensity	medium	0.4	short	100
			low	0.2	short	150
Notification	Generating another component	Medium intensity, medium sharpness, two short impulses	medium	0.4	short	50
Error	Implementation of a component meets the constraints	High intensity, sharp vibration, medium duration	high	1.0	middle	400
Success	The component is applied	Short burst of impulse, high intensity, medium sharpness	high	0.7	short	100
			high	0.7	short	150
Epic success	A milestone is accomplished	High intensity, medium sharpness	high	0.7	Short	100
Failure	A task is failed	Five short bursts of impulse with overlay, max intensity, high sharpness	high	1.0	short	200, 250, 300

Functional haptic feedback provides semantics related to reasoning in problem-solving, involving analytical tasks for planning. Of particular interest is the user's understanding of the relationships between design components in the physical space. An example of a relationship is the priority for construction, assembly, or installation of the design components in the physical space. Reasoning on the relationship demands spatial and temporal cognitive abilities (STCA). The aim of *functional* haptic feedback is to assist the user's reasoning (spatial and temporal reasoning) when required. An example is providing a better comprehension or awareness of the order for construction and assembly among two or more design components—by featuring STCA— as shown in Fig. 5a and 5b.



(a) Design components (as defined in the WBS)

(b) Spatial and temporal information on the design components: an instance of relationship among components

Fig. 6: Spatial and temporal reasoning on design components (using STCA).

Functional haptic feedback informs the user which elements possess the highest priority for their construction and assembly (i.e., some design elements have higher priority than others to make their construction feasible and efficient). ga, for instance, illustrates the building components— without any spatial and temporal information. Fig. b illustrates spatial and temporal information — the relationship among the objects in the physical space, by establishing the priority and order for their construction. Haptic code will help the learner to reason on spatial and temporal information using a combination of duration (D), granularity (G), intensity (I), and sharpness (S) features. For example, a combination of values from the parameters D, I, and S will inform the order distribution in a spectrum (e.g., from the lowest to the highest value or from the highest to the lowest value). Consequently, each component on the final level has its unique haptic code (DGIS) comprising values for each parameter.

The *functional haptic* (*vibrotactile*) *feedback* is related to information on the hierarchy of construction activity sequencing. Interaction with each component is assigned with unique feedback, which allows the user to easily discriminate the components one from another based on their semantics by selecting them from the WBS of the building (Fig. 2b). Due to the perceptive haptic nature of hands, functional haptics is assigned to the haptic gloves.

4. CONCLUSION

The presented study describes an exploration of new human-machine interactions to determine the effects of learning through the combined visual and haptic modalities in VR environments. The interactions with an immersive environment involve engineering design comprehension for planning activities— framed in a problem-solving task. The study presents the technology environment using VR and real-time haptic feedback for experiencing problem-solving tasks — by complementing semantics of visualizations (e.g., 3D designs) with haptic feedback (e.g., vibrations) for a CEM task.

The approach to building a VR environment with dual interactive mode (visual and haptic) facilitates the creation of new forms of understanding problems in planning, a highly cognitively demanding task where STCA plays a pivotal role. Learners map VR visual and haptic features to domain (CEM) problems and build solutions to the planning problem. They used VR technology (headset and controllers) to engage embodied perceptuomotor information by interacting with visual and haptic representations. For example, users navigate the 3D design in VR to approach locations of interest, allowing iterations between representations and reflection while problem-solving. In future work with a higher number of testing subjects, it is expected to demonstrate that haptic feedback (haptic code) effectively informs the learners of the semantics of the components for the planning task, enabling the learner to infer conditions in a virtual scene.

The technology's pedagogical features will make design information from multiple engineering specialties readily available for haptic and visual perception in a stepwise process to learn planning tasks. The technology will facilitate learning through observation and VR movements of design components. The approach uses work packets (construction product deliverables) that would enable scenarios of learning about understanding deliverables as chunks of workload for planning—the smallest unit that can be planned and managed for construction operations. By enabling learning with a work packet focus, the approach facilitates understanding of planning by framing control into a process (set of steps for delivery) of construction (assembly). The method provides opportunities for the learner to assimilate complex simulated realities of the physical space and develop spatial-temporal cognitive ability. Spatial-temporal ability allows learners to effectively manage and comprehend significant amounts of spatial (how design components are related to one another in the 3D space) and temporal (the logic in a process, such as the order, sequences, and hierarchies of the resources within a construction task) information.

The insights collected from this study underscore the significant potential of the VR and haptic cues to enhance the learners' perception of a problem's conditions that are not visible to the learner. Further exploration of technology experimentations will allow researchers to draw conclusions on the learners' perceptual competence and problem-solving capabilities, thereby contributing to the formation of project engineers with high levels of productivity in the construction industry.

5. ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grants No. (2044444), (2222870), and (2040422). Any opinions, findings, conclusions, or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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ENHANCING THE REALISM OF VIRTUAL CONSTRUCTION SAFETY TRAINING: INTEGRATION OF REAL-TIME LOCATION SYSTEMS FOR REAL-WORLD HAZARD SIMULATIONS

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ABSTRACT: *In numerous studies, virtual training for construction safety has been proposed as a promising approach. However, creating realistic training scenarios requires significant resources, encompassing various elements such as sound, graphics, agent behavior, and realistic hazards. Digital Twins have revolutionized this process, and although so far, on a conceptual level only, significantly reducing the associated workload, it is still not exploiting its full potential. In this work, we propose a novel approach that leverages Real-time Location Systems (RTLS) data to simulate the real-world behavior of construction workers and equipment within Virtual Training Environments (VTEs). We aim to create training scenarios with dynamic real-world instead of hardcoded made-up hazardous events. To achieve this, we propose an extension to our Digital Twin for Construction Safety (DTCS) framework that now integrates (a) trajectory data streams of construction personnel and equipment and (b) technical specifications of the construction site work environment, including location and geometry of terrain and surface objects, to simulate real-world hazards in virtual safety training scenarios. Our further contribution is a case study application to explore the DTCS training capacity. Applying a logical filtering algorithm, we can process the RTLS data and ensure that the movements of the workers and equipment within the virtual environment are as realistic and representative as within the real world. This then enables the creation of realistic hazards that trainees can encounter in the training phase. Preliminary results with trainees suggest that the proposed work can have a high potential to enhance the realism of safety training, especially when they need to experience human-machine-related interactions safely. However, further work is required to create more responsive learning environments where the equipment follows real trajectories but also responds intelligently to the trainees' actions. By leveraging real-time data and advanced visualization technologies, we bridge the gap between the physical and virtual realms, enabling trainees to interact and navigate within a realistic virtual environment.*

KEYWORDS: *Construction Safety, Digital Twins, Education and Training, Game Engines, Internet of Things, Learning Environments, Mixed and Virtual Reality, Real-Time-Location System, Real-world Hazards.*

1. INTRODUCTION

The numbers of occupational injuries and fatalities in the construction industry remain high despite significant investments in safety measures. Working on construction sites is one of the most fatal workplaces in the United States (BLS, 2022). The industry has introduced several approaches to increase safety. Generally, they can be separated into three categories: (1) Prevention through design and planning, (2) Right-time intervention, and (3) Prevention through training and education. Training in simulated environments has become more popular over the last few years. Among others, an advantage of virtual training is that the trainee can practice tasks in a safe environment without hazards where mistakes cannot lead to injuries. Several studies investigated virtual training for construction safety using Virtual Reality (VR) with head-mounted displays (Fang et al., 2014; Hilfert et al., 2016; Wolf et al., 2019; Jacobsen et al., 2022; Sacks et al., 2013; Jelonek et al., 2022), or desktop-based virtual training (Speiser & Teizer, 2023a). More recently, Bükrü et al. (2019) and Wolf et al. (2022) developed the concept of Augmented Virtuality (AV) in construction safety training. Noteworthy in their study is the use of real hand-powered tools to generate haptic control and feedback in a virtual learning environment made for construction trainees and not necessarily anymore for academic student participants. These studies highlight that it requires significant efforts to create such training environments independently of the used technology. To ease the creation of the training environment, Golovina et al. (2019a) use Building Information Modelling (BIM), and our previous research introduced a data model for a digital twin, indicating a significant decrease in resources for generating the training scenes (Speiser & Teizer, 2023b). Still, most studies developed hard-coded scenarios where hazards are artificial. Hence, there is potential for more realism with less effort by including additional data sources and realistic hazards.

Despite VR being adopted in various industries, the terminology remains ill-defined. VR is often associated with an immersive experience using head-mounted displays. Some studies consider desktop-based experiences as VR (Wang et al., 2018), while others speak of fully immersed systems that utilize a head-mounted display (Kim et al.,

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Kilian Speiser, Kepeng Hong, Jochen Teizer, *Enhancing the Realism of Virtual Construction Safety Training: Integration of Real-Time Location Systems for Real-World Hazard Simulations,* pp. 155-166, DOI 10.36253/979-12-215-0289-3.15

2017). Milgram et al. (1994) first introduced a continuum describing the different mixtures of reality and virtuality. In this continuum, VR defines an environment where only virtual elements exist. At the same time, Augmented Reality (AR) describes systems where most elements are real and a few are virtual. This continuum intended to classify Mixed Reality (MR) experiences with visual displays. However, since 1994, several studies have developed other kinds of displays to include haptics (Azmandian et al., 2016), multidimensional sound (Savioja & Svensson, 2015), and scent (Yanagida, 2012). Integrating such displays creates a new level of immersion.

Based on the latest developments, Skarbez et al. (2021) revisited the continuum from Milgram et al. (1994) and proposed new indicators considering the latest developments in new technologies: (1) the *Extent of World Knowledge (EWK)*, (2) *IMmersion (IM)*, and (3) *COherence (CO)*. The system's immersion defines the level of immersive feedback to actions. Skarbez et al. (2021) conclude that a fully immersive system must realistically respond to all human senses. *EWK* describes what objects are part of the virtual experience and how they are represented. Nowadays, the Internet of Things (IoT) can provide advanced information and replicate real elements in virtuality more accurately. *CO* indicates how consistently the system reacts to the users' intentions. Game engines provide functionalities such as realistic lighting or gravity to make virtual environments coherent.

As mentioned before, creating virtual training in construction safety is time-consuming and requires realistic hazards. Much of the work is dedicated to developing realistic training scenarios where machines perform realistic tasks and move accordingly to represent realistic hazards. IoT can provide such real-world data, and game engines provide real-world physics to achieve coherent experiences. While previous studies have used game engines for creating virtual experiences, no previous work integrated real-world hazards from IoT devices. This study proposes a novel method for bridging this gap by streaming data from IoT devices into a Virtual Training Environment (VTE). The objective is to create more realistic training scenarios with hazards from real-world data. The method increases the *EWK* as well as the *CO* of these systems. The remainder of this paper describes the relevant research gap and introduces the framework integrating IoT devices. Second, a case study validates the proposed method using two training scenarios before summarizing the results and concluding with future work.

2. RELATED WORK AND IDENTIFIED RESEARCH GAP

While virtual training for construction safety has shown promise in improving workers' safety awareness (Adami et al., 2023), a significant research gap exists. The current state of virtual training for construction workers lacks the integration of real-world data from IoT devices, which hinders higher levels of realism in the training experiences. A literature review revealed that studies have explored the use of game engines for simulating real-world physics (Juang et al., 2011), BIM (Golovina & Teizer, 2022), and digital twins (Speiser & Teizer, 2023a; Teizer et al., 2024) to create virtual training scenarios for construction safety. These approaches have enabled the development of more interactive and immersive training environments, allowing trainees to practice tasks safely. However, to date, no previous work has integrated real-world data obtained through IoT into virtual safety training to expose the trainees to realistic hazards despite the potential benefits (Salinas et al., 2022; Zoleykani et al., 2023).

Several studies on Real-Time-Location-Systems (RTLS) exist in construction as they can monitor the precise location of objects. Park et al. (2017) detected hazard exposure in workers using Bluetooth Low Energy (BLE), a technology enabling low-power communication between devices. Chae & Yoshida (2010) introduced an approach to prevent collisions with heavy construction machinery using radio-frequency identification (RFID). Teizer et al. (2008) used Ultra Wideband (UWB) for tracking construction resources and later for visualizing worker and gantry crane trajectory data in a first-of-a-time real-time VR learning environment for ironworker trainees (Teizer et al., 2013). Narumi et al. (2018) stressed the applicability of Real-Time-Kinematic Global Navigation Satellite Systems (RTK-GNSS) for teleoperating construction equipment.

This research bridges the research gap and unlocks crucial advantages by incorporating real-world data from RTLS devices into the VTEs. First, the IoT data will significantly increase the realism of the training simulations as the trainees virtually experience accurate information about the construction site conditions, worker locations, and equipment status. Second, the IoT data will enable the realistic reproduction of hazardous events for the trainee and, therefore, make the performance assessment more meaningful. Third, processing the data with appropriate algorithms will enhance the coherence. Construction sites are dynamic environments with numerous interacting elements. Incorporating data from IoT devices will allow the VTE to respond dynamically to changes in real-world conditions, thereby creating more coherent and contextually relevant training experiences.

In summary, the identified research gap is the lack of integrating real-world data from IoT devices into VTEs for construction safety. The proposed research aims to address this gap by developing a novel method that leverages RTLS data to enhance the realism, coherence, and practicality of virtual training scenarios, ultimately contributing to improved safety measures and reduced occupational injuries and fatalities in the construction industry.

3. DIGITAL TWIN FRAMEWORK AND REAL-TIME DATA PROCESSING

Figure 1 illustrates the proposed framework enabling real-time training for construction safety that is based on the DTCS proposed by Teizer et al. (2024) but focuses on components related to virtual training.

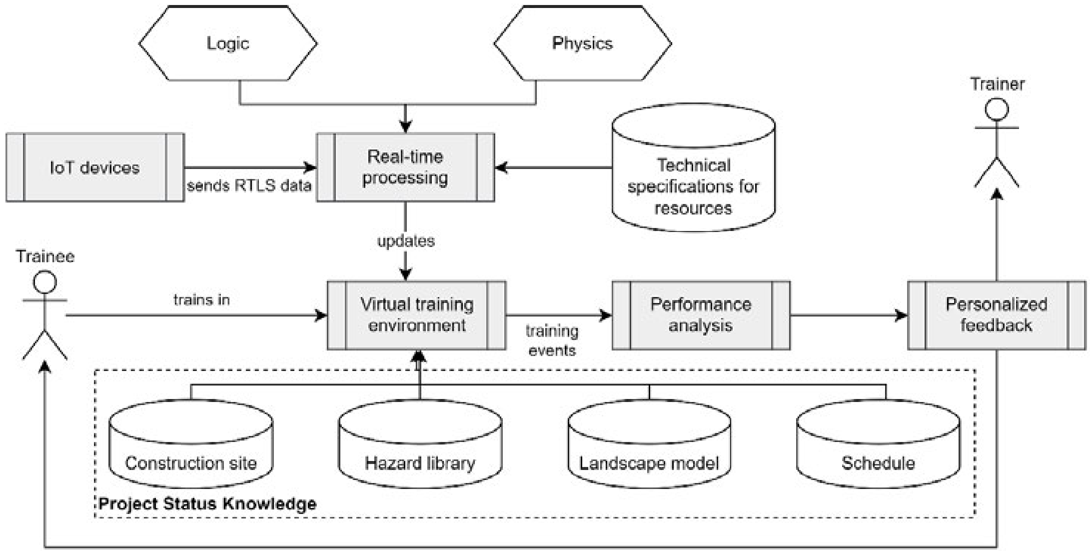

Fig. 1: Digital Twin framework integrating IoT data into virtual training environments.

3.1 Input data

The core of the framework is the VTE that utilizes the Project Status Knowledge (PSK) from the DTCS to virtually represent the construction site. The PSK contains the BIM model, a landscape model, the required resources, and a construction schedule. The PSK also encompasses a hazard library defining currently existing hazards such as restricted working areas, fall hazards, or moving machinery. These hazard zones geometrically describe areas where workers are in danger. Our previous work proposed a data model integrating hazards and safety regulations in a VTE (Speiser & Teizer, 2023b). The hazards can either be automatically detected by algorithms evaluating the PSK using safety regulations or can be modeled manually. This framework assumes that the VTE receives geometrically representable hazard zones. The landscape model contributes to realism by providing real surroundings. The requirements for the landscape model only concern the geometry for rendering purposes. For instance, a mesh from photogrammetry or laser scans may suffice.

3.2 RTLS data processing

The core novelty of this study represents the integration of real-world resources into the VTE to enhance realism through EWK and CO. Such resources include human workers, machinery, or materials. This work focuses on human workers and heavy machinery, such as wheel loaders or excavators. The representation of these resources in the virtual world utilizes geometrical descriptions as well as RTLS sensors to localize the resources in real-time. We expect the framework to function for all types of RTLS systems once the data quality is at a high level.

RTLS data provides spatial-temporal information, which allows us to localize a resource at a timestamp. This information increases the EWK of the virtual environment as the virtual objects are placed at the real location. However, RTLS does not provide further knowledge about the state of the resource (e.g., orientation of the resource). Such knowledge is essential for MR experiences to generate coherent experiences. The real-time processing module generates knowledge about the state of a resource and simulates the motions realistically using technical specifications of individual resources, physics, and logic.

The technical specifications help to create a realistic object of the resource and load it into the MR scene. Besides the correct geometry, it also includes the possible motions of the resource. For instance, how does a machine steer, or can the machine move backward? *The Real-time Processing* module utilizes this information together with physics and logic statements to simulate the motions of the resources realistically. Physics integrates physical laws such as gravity or sound emissions, and the logic statements exclude irrational simulations. For instance, a railway wagon cannot rotate by 180° but changes direction, while a forklift may rotate by 180° without moving the location. The real-time processing module prioritizes realistic visualizations over the accuracy of the sensor data. We would rather misplace the element by a tolerance compared to the recorded data simulating abrupt motions.

3.3 Output: Performance assessment and personalized feedback

The performance analysis module collects data on how the trainee interacts with hazards throughout the training experience. Utilizing the hazard library based on safety regulations, this module constantly checks for violations of safety rules from the trainee. Once such violations are detected, further algorithms can evaluate the severity of the violation. For instance, Golovina et al. (2019b) introduced an approach to classify safety violations. To implement such a method in this framework, the digital twin must provide the location and geometry of hazard zones. Previous research has proposed virtual training for collecting such data (Golovina & Teizer, 2022).

Once the training ends, the performance data is processed, and personalized feedback is generated. Personalized feedback to trainees has various benefits. Among others, learning has shown better efficiency when trainees understand what they did and how they can improve (Pianta et al., 2012). The feedback must summarise and assess the trainee's performance and graphically describe potential improvements. The feedback is also shared with the trainer, who can compare different performances.

4. CASE STUDY

To validate the proposed framework, we conducted an experiment in an infrastructure project in Munich, Germany. The study comprises five steps: (1) Collecting RTLS data from construction resources, (2) generating the game scene in Unity, (3) processing the RTLS data, (4) simulating the resources in the Unity scene using the processed data, and (5) evaluation of the simulation. The following sections describe how we tested the framework and finished with the required changes in order to provide (near) real-time training.

4.1 Reality: RTLS data collection

We collected the RTLS data at the staging area for a subway track replacement project in Munich. The collection lasted for three days during the early stage of the project. During the collection, we observed and tracked multiple tasks, such as unloading materials from the truck and arranging and loading materials onto rail cars. The tasks involved resources of both pedestrian workers and construction equipment.

The RTK-GNSS solution was used for the location data collection as it performs accurately in outdoor environments. The RTK-GNSS solution consists of two components: a base station and rovers. The base station is placed statically in open space, and workers and equipment carry the rovers. Compared to a single GNSS solution whose accuracy is affected by atmospheric delays or clock errors, the RTK-GNSS uses the base station to provide correction for rovers so that the workers and equipment are located with cm-level accuracy (Wielgocka et al., 2021). The accurate location information reduces the work of data processing and filtering when importing it into the training environment. In addition, it can cover a wider tracking area with a simple setup than other locating methods such as BLE or UWB.

Given that traffic from rail cars and construction equipment occurred within a limited area, the logistics at the staging area could be packed and complicated. Therefore, pedestrian workers must receive sufficient realistic safety training to train to work in such an environment. To test the proposed framework, we recorded a task where two construction workers moved materials from a storage area to a rail wagon. Figure 2 illustrates the scenario: One worker operates a forklift, and the other worker assists the equipment operator. The work lasted for 90 minutes. The pedestrian worker carries an RTK-GNSS module, and the forklift has a module mounted on the roof of the forklift, centrally placed on top of the operator's seat.

Fig. 2: The forklift moves material from the loading area to a railway wagon while a pedestrian worker assists.

Figure 3a shows the trajectories of the two resources during the 90 minutes. The RTK-GNSS rovers streamed the location data to a database with a frequency of 5Hz for the machine and 1Hz for the worker. During that time, the worker supported the equipment operator by attaching the material bags to the forklift in the loading area and removing them in the unloading area. Figure 3 shows that frequent interactions between workers and equipment were inevitable when working simultaneously in a limited area. The 3D plot in Figure 3b visualizes the 2-dimensional movements of the forklift and the worker over time within the loading area to stress the close interaction between the forklift and the worker. This visual eases the spotting of proximity events, which entail that the worker was too close to the forklift. In this study, we defined too close proximity once a worker enters a bounding box with a one-meter distance to each side of the forklift. We ran an analysis based on an existing approach to detect such proximity events (Golovina et al., 2019b). The worker entered the 1m bounding box 28 times during the time. We will use this performance as a reference for the trainees in our training scenarios, but the results also indicate that this framework is also applicable for safety monitoring or assessment of construction resources as the game engines provide large libraries for the demand of the previously mentioned applications.

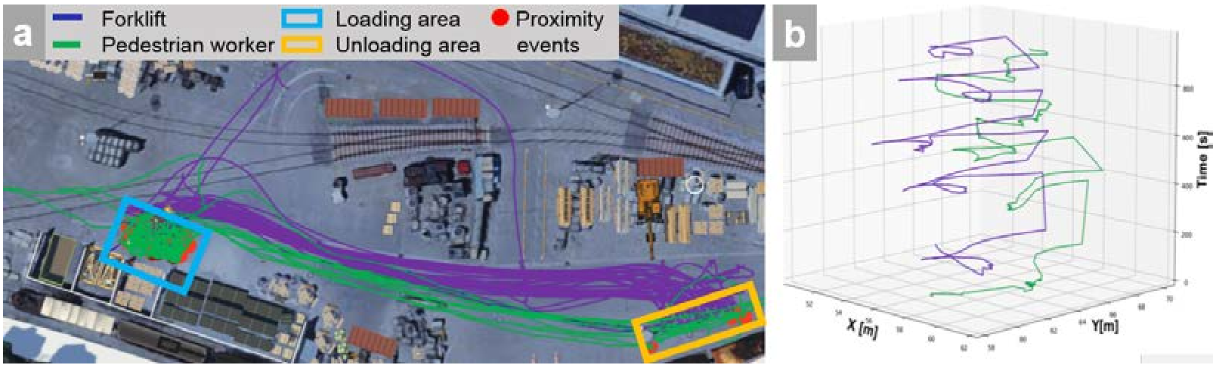

Fig. 3: (a) 2D-trajectories of the forklift and the worker during a work task over 90 minutes with 28 proximity events, and (b) the trajectories, including the time-axis limited to the unloading area for 15 minutes.

4.2 From reality to virtuality: RTLS data processing

The collected data consists of a set of locations (x,y,z) with the corresponding timestamps. The locations refer to the coordinate system WGS84, a common GNSS localization system. As the Unity scene refers to ETRS89, we transformed the WGS84 data into ETRS89 using Pyproj (Pyproj Contributors, 2023). Based on this data, we can visualize the individual states for each recorded point in the Unity scene and locate it at the real-world location. The second component of data processing connects the individual points and moves the resource coherently with a realistic speed, orientation, and motions. For instance, the wheels rotate, or the axle turns once steering. Figure 4 illustrates a problem: The trajectory from a machine implies that the machine first moved forward, then stopped, and returned backward. To include such logic in the framework, we need to make assumptions and technically convert them into an algorithm. This specific forklift steers with the rear axle, which must also be considered when simulating the motions. We make the following logical propositions:

Proposition 1: The forklift only moves forward or backward and not sidewards.
Proposition 2: The forklift changes directions if and only if it is moving.
Proposition 3: The wheel of the forklift spins if and only if the forklift is moving.
Proposition 4: A pedestrian worker only walks forward.
Proposition 5: Distances of less than 10 cm between consecutive points are considered noise.

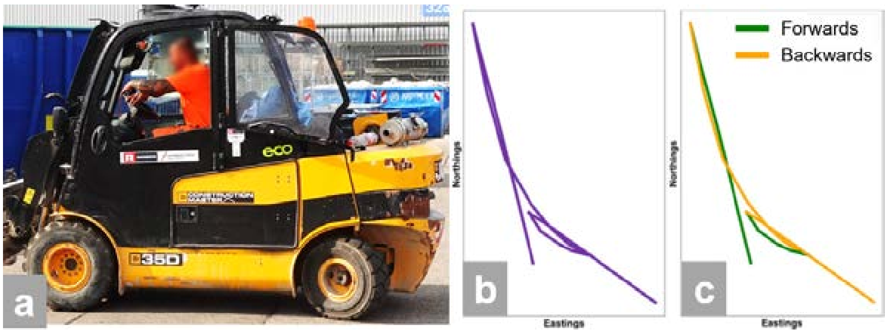

Fig. 4: (a) the tracked forklift, (b) the recorded trajectory, and (c) the directed trajectory after the assessment.

Some of these assumptions are not precise. For instance, humans can walk backward or sidewards, crawl, and jump, but it is rather difficult to detect such behavior purely based on the trajectory of a human. Hence, we limit the scope to forwards walking humans. The last assumption was made after the first implementation, where the authors noticed that the smoothness of the motions appears faulty when considering short movements. For instance, the worker probably standing would constantly change direction and move by a few centimeters. The following algorithm integrates these logical statements and moves the resources in the correct direction at a given speed.

Algorithm 1: Move object

```
Input: Resource, CurrentPoint, NextPoint, CurrentDirection
1    Distance = |(NextPoint – CurrentPoint)|
2    If Distance >= 0.1:
3        NextDirection = NextPoint-CurrentPoint
4        Duration = NextPoint.Time – CurrentPoint.Time
5        Velocity = Distance/Duration
6        If Resource is Machine:
7            If |AngleBetween(CurrentDirection,NextDirection)| > PI/4
8                MoveBackwards(NextPoint, Velocity)
9            Else MoveForwards(NextPoint, Velocity)
10       Else MoveForwards(NextPoint, Velocity)
```

The proposed algorithm moves a resource to the next point with realistic speed and rotation. If the next point is at least 10 centimeters from the current location, the algorithm determines the required direction and the velocity. Depending on whether the resource is a machine or a human, the algorithms move the resource forward or backward. The methods *MoveForwards* and *MoveBackwards* in lines 7, 9, and 10 implement how the resource behaves when moving. Practically, this means that the resource is moved in every frame according to the velocity and distance. The methods also implement additional animations such as rotating wheels of the machine or body motions for the worker (moving the legs, swinging the arms).

4.3 Virtuality: Training scene

The virtual environment was generated in the game engine Unity. We used Unity as it provides a vast selection of assets and is simpler for conceptual work, while other game engines like Unreal outperform Unity with the graphics. The virtual environment comprises the components illustrated in Figure 5: (1) a landscape, (2) the BIM model, (3) additional objects to enhance the realism of the game scene, and (4) the moving resources connected to IoT devices.

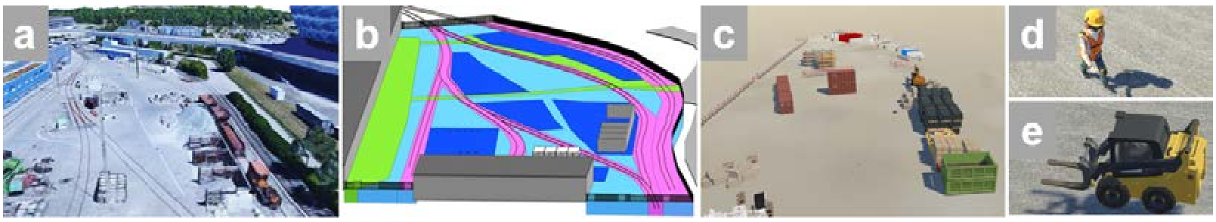

Fig. 5: Scene components: (a) landscape, (b) BIM model, (c) site equipment, (d) human worker, and (e) forklift.

Google's photorealistic tiles were added to the Unity scene using the asset Cesium to visualize realistic surroundings. This asset allows for adding geo-referenced objects and utilizes the WGS84 coordinate system, which is commonly used in GNSS applications. The tiles from Google shown in Figure 5a have two disadvantages: First, it is outdated, and second, the quality is low. For this use case, we consider it sufficient as it is not the focus of this study. A frequently updated mesh generated from a laser scan or photogrammetry may increase realism and ensure up-to-date surroundings. In the next step, we added the BIM model in the form of an IFC file. We envision the digital twin to provide BIM models of high quality. In this case study, a BIM model with few elements and a low level of development was available. The provided BIM model contains the physical structure of the site (see Fig. 5). A modified version of the Unity Asset *IfcImporter* was used to convert the IFC file into a Unity-readable format. The provided IFC file references the geospatial coordinate system ETRS89. Hence, the origin of the BIM model was converted into WGS84 to place it correctly within the landscape model. The local origin of the Unity scene still relates to the ETRS89 origin of the BIM model. In this way, we refer to a Cartesian coordinate system and no longer to the geographic coordinate system WGS84, which eases simulating the resource. In the third step, the scene obtained additional objects to make the environment more realistic. Based on a site visit and a site layout plan, we added elements such as an office trailer, safety guardrails, or material storage. The site layout plan defines, among others, safe paths for the workers and spaces for the machines to operate. In the last step, the tracked resources are added, and the movements will be simulated based on the collected trajectories and the proposed algorithm in the previous sections. The moving resources represent the hazard for the workers, and as they are following the real-world data, the simulation is more realistic.

5. EVALUATION

The introduction described the problem of this research: Generating realistic scenarios for construction safety requires realistic hazards and realistic surroundings. Our framework proposes the use of RTLS data for integrating scenarios based on real tasks. The framework was implemented for the described construction site and tested with the 90 minutes data sample from the previous section in two training scenarios: (1) a training experiment with a student to validate that the created hazards are more realistic, and (2) collaborative tasks where the trainee assists the forklift. Before describing the training scenarios, an accuracy assessment evaluated the algorithm, simulating the motions of the resources.

5.1 Assessment of simulated data

We evaluate the accuracy of the RTLS data integration based on two indicators. First, we measure the deviation from the simulated data to the collected data in the real world. Second, we visually assessed the simulated data and compared it to a video recording.

One of the main objectives of this work was to simulate hazards realistically using RTLS data. RTK-GNSS provides reliable and accurate data. However, the filtering algorithm processes the raw data to visualize motions coherently. This can generate misplaced hazards. Hence, the filtering algorithm was evaluated by comparing both the virtual trajectory to the real trajectory. For collecting the virtual trajectory, a Unity script streamed the location of the resource with 10Hz to a database. The virtual trajectory was then compared to the real trajectory. As the real trajectory was collected with 5Hz and 1Hz for the forklift and the machine, respectively, the time-wise closest point from the virtual trajectory was compared to the real point. There is already a little error in this comparison as the closest point can be up to 100ms apart. With a maximum speed of 30km/h, this can contribute to inaccuracy of up to 8.5cm.

Table 1 summarizes the distribution of the deviation for both the worker and the forklift. The algorithm for the worker provides accurate results. With a standard deviation of 5.9cm and a 99 percentile of 29cm, the performance is very good. However, it is important to stress that the data was collected with 1Hz. The implemented algorithm aims to simulate the movements towards a given point. In between these points, we do not have evidence of what happened. Within this second, we do not know whether the worker turned around. Thus, data should be collected with a higher frequency in order to evaluate the realism of the simulation better. The accuracy of the simulation for the forklift is more meaningful for two reasons: The real-world data was collected with a higher frequency, and the algorithm moves the resource on interpolated paths, which entails a higher deviation. The mean deviation amounts to 13cm, and the standard deviation is 27cm. The median deviation amounts to 6.8cm, and the forklift was at least 40cm accurate during 95% of the time. The inaccuracy of the simulation relates to the low frequency of the collected data points. The authors conclude that a higher 30-100Hz frequency will enable a more reliable simulation.

Table 1: Deviations between the real trajectory from the RTLS data and the virtual trajectory.

Resource	Mean	Standard	Median	95 percentile	99 percentile
Forklift	13cm	27cm	6.8cm	40cm	46cm
Worker	10cm	5.9cm	7.6cm	21cm	29cm

The second measure to evaluate the simulation was conducted manually. We compared 10 minutes of the simulation to a 7-minute video recorded on-site simultaneously. The video reveals that twice during the 10 minutes, the forklift was simulated moving backward while it was actually driving forward. This happened during a total time of 28 seconds, corresponding to 6.2%. Comparing the movements of the worker compared to the simulation seemed realistic.

5.2 Training Scenario 1: Simultaneous tasks

As we mentioned previously, virtual construction safety training requires personalized feedback. Research has proposed methods for collecting such data and can visualize it in a concise way for construction workers. In this research, we use the concept of safety parameters and collect data from the trainees when entering hazards using automatic data collection. In the same way as before with the worker in Section 4.1, a proximity event is triggered once the trainee enters the bounding box around the forklift.

In the first training scenario, the trainee must collect various objects in the training scene and return them to a storage area. Meanwhile, the forklift and the pedestrian worker will follow the trajectories from the real-world data collection. During the training, the trainee needs to ensure that they will not trigger any hazards relating to the forklift. Figure 6a indicates such a situation: The trainee needs to cross while the forklift passes. Should the trainee get too close to the forklift, a close call is triggered, and data will be collected, which is processed for personalized feedback. The created training scenario lasts 10 minutes, where the trainee needs to collect seven objects. Figure 6b shows the results. The trainee crossed the road six times while the forklift was nearby. The visual indicates that the worker always identified the forklift while heading east. However, returning, the trainee was very close to the forklift twice. This data allows us to conclude that either the equipment operator should have more distance to the pedestrian cross or that the trainee could not see the forklift. Figure 6b also depicts the three proximity events of the real-world worker during this 10-minute excerpt.

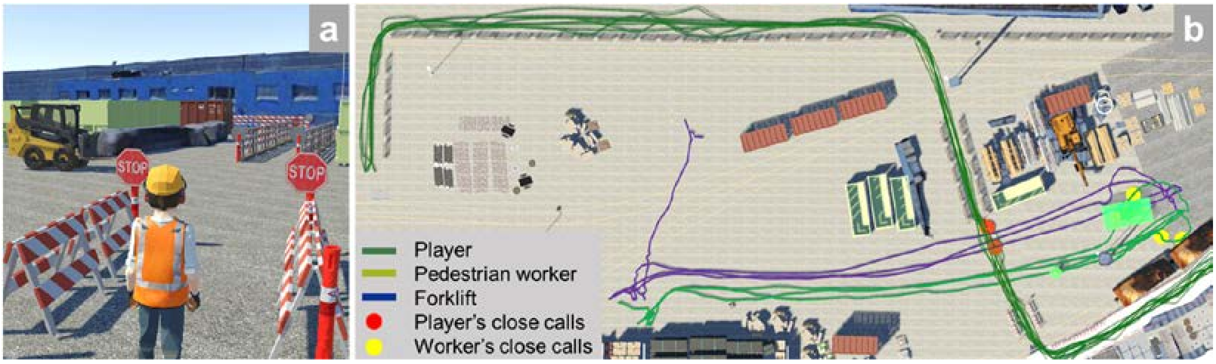

Fig. 6: (a) Results of the first training scene, including the landscape, BIM model, resources, and trajectories from IoT devices, and (b) the trainee crossing the road while the forklift follows the real-world trajectory.

5.3 Training Scenario 2: Collaborative task

In the second training scenario, the trainee takes over the role of the worker. Hence, the pedestrian worker is removed from the game, and the trainee is advised to support the equipment operator in loading the forklift. The trainee must wait for the forklift and assemble the boxes by pressing "C" on the keyboard. To ensure the worker is safe, the trainee is advised to wait in highlighted areas to not collide with the machine. Figure 7b illustrates the safe area, and Figure 7a shows the results from the 90-minute task. During the 90 minutes, the worker followed the forklift to assist in transporting the boxes. We collected the data about the proximity with the forklift using the 1m bounding box described before. When the worker collides with the bounding box, a proximity event is triggered. Figure 7a shows the 37 collisions with the bounding box in yellow and highlights three actual hits in red. The figure indicates that the actual hits occurred not in the loading area but when the forklift was approaching the worker while the worker walked to the unloading area. The forklift was emitting sound, and the game engine increased the volume when coming closer to the sound source. Still, the worker did not avoid the equipment.

However, it is likely that in real-world situations, the equipment operator would have stopped. These collisions are not realistic and reveal one major disadvantage of this approach: The machine is following the trajectory without reasoning. Hence, future work needs to investigate how to include such reasoning as the machine would most likely avoid the machine. Comparing the virtual performance of the trainee to the real-world worker, the trainee triggered more proximity events. There can be different reasons, but all yellow proximity events were triggered at the front. A reason could be that the forklift was stubbornly following the trajectory from the data collection and did not interact with the worker. There was no communication possible between the forklift operator and the construction worker. Hence, if the worker, for instance, did not finish, yet, mounting the box, the forklift will yet continue on the route and almost hit the worker. The authors propose two approaches to tackling this issue. First, the forklift may include intelligence, such as avoiding the worker while driving or waiting for the trainee to finish their task before moving. Second, a multiplayer game where another trainee takes over the role of the equipment operator could enhance realism and improve collaboration between the workforce.

Fig. 7: The (a) results from Training Scenario 2 indicating the trajectories and proximity events, and (b) safe waiting areas where the trainee can safely wait for the return of the forklift until its standstill.

6. CONCLUSIONS AND FUTURE WORK

In this paper, we addressed the challenge of creating realistic virtual training scenarios for construction safety. Despite the advancements in virtual learning, the integration of real-world data from IoT devices was largely missing, hindering the level of realism regarding hazardous situations. Our proposed framework leverages RTLS data to enhance the extent of world knowledge and coherence of VTEs, resulting in more realistic and contextually relevant experiences as the hazards relate to real-world scenarios.

Through a case study conducted at a construction site in Munich, Germany, we validated the effectiveness of our framework. The integration of RTLS data allowed us to accurately represent the movements of construction workers and equipment within the virtual learning environment for safety training purposes. The data processing algorithms and logical propositions ensured realistic motions of the resources, further enhancing the coherence of the virtual environment. Additionally, we demonstrated the practicality of the proposed method by creating a realistic training scenario involving hazardous interactions between construction workers and equipment. The study also indicates potential in creating training scenarios for collaborative tasks between humans and equipment based on real-world data.

Nevertheless, the framework requires a more responsive simulation where the equipment not only follows a real path but can also stop and continue based on the trainees' behavior and feedback or avoid them when having clear sight. It also raises further research questions, for example, whether it would be better to create multiplayer games for collaborative work tasks rather than making equipment follow realistic but, eventually, for human learners, predictable travel routes. As work is underway, expanding our framework to support multiple trainees interacting and collaborating within the virtual environment would foster a more dynamic and engaging training experience, mirroring real-world construction sites' teamwork and coordination.

This preliminary work successfully bridged the gap in virtual training for construction safety by integrating real-world data from IoT devices, but there are several avenues for future improvements: RTLS data should be recorded at a higher frequency than 1Hz, and additional sensors on relevant static or dynamic objects in the scenery could further enhance the realism. For the forklift, additional sensors could detect the vehicle's orientation or the fork's exact location and extension. This would ease the simulation of movements. In addition, a Body Motion Suit (BMS) for the construction worker may provide more information on how the worker executes a specific task, adding a high level of perhaps needed detail of relevance to some construction hazards.

In conclusion, our preliminary research efforts contribute to the advancement of virtual training for construction safety by leveraging IoT data to create more realistic and coherent training scenarios. As we continue to explore and refine the proposed framework, it has the potential to significantly improve safety awareness and reduce occupational injuries and fatalities in the construction industry.

7. ACKNOWLEDGEMENT

This research has been funded by the European Union Horizon 2020 research and innovation program under grant agreement no. 95398.

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VISIBILITY ENHANCEMENT OF CRANE OPERATORS USING BIM-BASED DIMINISHED REALITY

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ABSTRACT: *The limited visibility experienced by crane operators in construction sites poses significant challenges, leading to reduced performance and safety concerns. Obstructive elements, such as existing buildings, construction elements, or vehicles, can block the crane operator's field of view, hindering their ability to execute lifting operations with precision and confidence. To address this issue, this study presents a novel approach using Building Information Modelling (BIM)-based diminished reality (DR) to enhance visibility by dynamically removing obstructive objects from the crane operator's perspective in real-time. The research employs a marker-based registration system that effectively aligns BIM data with the physical environment, ensuring realistic and precise DR visualization. Additionally, a semi-automatic selection method that involves minimal intervention from the user is employed to select desired objects. To generate the background, the system utilizes real-time observation data from occluded areas. A validation through a case study demonstrates the practical applicability of the developed system in real-life construction scenarios.*

KEYWORDS: *Diminished Reality (DR), Augmented Reality (AR), Mixed Reality (MR), Crane, Visibility, Building Information Modelling (BIM), HoloLens, Construction industry.*

1. INTRODUCTION

Construction sites are inherently hazardous environments due to the presence of heavy machinery and large equipment. Among these, cranes play a vital role in the construction process. Crane operators may be required to operate when they do not have direct visibility of the load, which is referred to as a "blind lift". This type of lift has been recognized by the industry as one of the most hazardous activities, as it poses a significant threat to both personnel and nearby property. In general, reduced visibility in the working area can lead to lower operator efficiency and have an adverse impact on both the end product's quality and overall productivity (Price et al., 2021).

Diminished Reality (DR) has emerged as an effective solution for overcoming occlusions by recovering background scenes and giving an unobstructed view of the workspace. Meanwhile, Building Information Modeling (BIM), which is a digital representation of the building geometry and information (ISO, 2015), can be beneficial in the DR process. BIM can integrate data from various data-capture technologies, such as laser scanners, Global Positioning System (GPS), and imaging sensors, to provide complete data about a construction project (Alizadehsalehi & Yitmen, 2016). Considering these features, BIM data can be used to create a digital representation of the background scene that is required in the DR process.

In this study, we investigate the implementation of BIM-based DR to enhance crane operator visibility. Our proposed approach aims to facilitate a safer and more efficient construction environment by providing crane operators with a clear and unobstructed view of their work area. By utilizing BIM data and DR technology, we seek to improve awareness, empower operators to make informed decisions, and to elevate safety within the construction industry. The integration of BIM and DR holds the potential to significantly improve crane operations and enhance overall productivity and safety at construction sites.

2. RELATED WORKS

2.1 Occlusion handling in crane operations

Various technologies have been developed to handle occlusion and to enhance visibility for crane operators. The most widespread approach used by the industry is to ensure that the crane operator remains in constant radio communication with either a rigger or a signal person, who can provide guidance throughout the lift. However, these methods of communication can be unreliable and cause various accidents (Mansoor et al., 2023). Many solutions have been developed to overcome this limitation and improve safety and efficiency at construction sites. For example, a crane monitoring system is presented in (Price et al., 2021) that can provide the crane operator with real-time 3D visualization and the ability to give and receive feedback during blind lift tasks. In this study, the safety warning system is also created based on a 3D model of the crane environment. This 3D model is developed

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Roghieh Eskandari, Ali Motamedi, *Visibility Enhancement of Crane Operators Using BIM-Based Diminished Reality,* pp. 167-174, © 2023 Author(s),
CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.16

in real-time utilizing sensors, cameras, and laser scanners. An alternative approach involves the visualization of information using transparent displays (Sitompul et al., 2020). This information, which includes important details such as the height and weight of the lift, is displayed through head-down displays, which are installed near the operator's line of sight in the cabin. However, research has indicated that operators often pay minimal attention to the information presented on head-down displays (Wallmyr, 2017). This is primarily due to the placement of these displays far from the operator's line of sight, as they are positioned in a way that avoids hindering the operators' view. A major drawback of using these techniques is that a user is unable to view the information from their own point of view.

2.2 Augmented reality in crane operations

Augmented Reality (AR) can be used to combine computer-generated information with the user's view of the environment. AR systems may give the operator real-time feedback by superimposing valuable information such as the load weight, distance to the target, and other crucial data on their field of view, making AR a valuable tool for improving visibility for the crane operator, the surrounding area, and the operation to be carried out (Sitompul & Wallmyr, 2019). For example, (Yang et al., 2015) developed an AR system to assist operators by providing visual information, such as arrows. The findings indicated that the implementation of AR support led to a significant reduction in task completion time, as it allowed operators to perceive the environment more clearly and effectively. Moreover, it minimized collision frequency and enhanced the overall user experience, demonstrating the usefulness of AR in familiarizing operators with new environments (Yang et al., 2015).

Nonetheless, despite the numerous benefits of AR techniques in crane operations, there are certain limitations that can be overcome by Mixed Reality (MR) techniques. One of the disadvantages of AR is that it may suffer from limited depth perception and occlusion issues. In AR systems, virtual objects are superimposed onto the user's view of the real world, but they may not always appear in the correct position relative to real-world objects, leading to misinterpretations and potential hazards (X. Li et al., 2018).

(H. Li et al., 2022) presents a novel application of MR technology in the form of a night hoisting assistance system, highlighting the potential of MR for enhancing visibility and operational safety in crane operations. This system enables operators to perceive and interact with a virtual model of the hoisting process in real-time. The system offers variety of interaction modalities, including voice interaction, gesture recognition, and gaze tracking, allowing operators to intuitively manage and navigate the virtual environment.

2.3 Diminished Reality

Diminished Reality (DR), which is an advanced visualization technology for removing or reducing the visibility of objects in real-time, can go a step further by visually removing obstructive objects such as buildings, trees, or other equipment that may obstruct the operator's view of the workspace (Mori et al., 2017). Thus, DR can provide new opportunities for more accurate visualization for operators of heavy machinery such as cranes. (Aromaa et al., 2020) introduced the concept of DR for generating see-through visualization, allowing the operator to perceive the machine's physical structure as transparent from their viewpoint (see Fig. 1 (a)). Instead of making the machine's cabin transparent, (Palonen et al., 2017) developed an alternative method for visualizing the view in front of the machine using point clouds (see Fig. 1 (b)).

(a) (b)

Fig. 1. (a) See-through visualization of the boom presented in (Aromaa et al., 2020) , (b) Visualization of the environment using point cloud presented in (Palonen et al., 2017)

Implementing effective DR solutions for operator visibility enhancement comes with a set of challenges that researchers and developers need to address. The main challenge of DR is obtaining reliable and accurate information about the hidden background, especially in dynamic construction sites where the surroundings may change frequently. Since DR aims to remove or reduce the visibility of obstructive objects, it requires access to real-time observation data or an accurate representation of the background scene to create a seamless visualization. Another challenge is the precise alignment of the virtual model with the real-world environment. For effective DR visualization, the virtual model must be accurately registered with the physical scene to ensure a seamless blend between the two. Achieving precise alignment often requires robust marker-based registration methods or other sophisticated tracking techniques, which can be complex to implement and may require specialized hardware or software. Furthermore, in scenarios where the background scene is dynamic and constantly changing, maintaining real-time updates of the hidden background information becomes critical. The DR system must continuously receive and process the latest observation data to accurately reflect any changes in the environment. This real-time processing can place significant computational demands on the system, requiring efficient algorithms and powerful hardware to handle the data in a timely manner. Overcoming these challenges and creating a seamless DR experience for crane operators requires sophisticated data processing techniques and a good understanding of the specific requirements of the construction site environment.

3. PROPOSED DR SYSTEM

The proposed system for enhancing crane operator visibility using BIM-based diminished reality allows for the seamless alignment of physical and virtual scenes, enabling the visualization of occluding objects and their removal from the crane operator's view in an MR environment. This approach aims to enhance visibility, safety, and situational awareness for crane operators in real-life construction scenarios.

Using our proposed system, the crane operator, who controls the overhead crane from the shop floor and is equipped with a head-mounted display, interacts with the system using hand gestures to visually remove the sections where obstructive objects are present. The process begins with scanning the QR code markers, followed by alignment of the 3D virtual model onto the physical scene. Subsequently, specific objects within the virtual model can be selected. Afterward, the system seamlessly integrates the real-time video feed from CCTV cameras, showing the dynamic real-time background and further enhancing the operator's field of vision.

The system architecture consists of three main layers, as illustrated in Fig. 2. The first layer involves data collection. The BIM model provides additional contextual information, such as the physical layout of the construction site, the positions of obstructive objects, the dimensions, and characteristics of the crane. The laser scanning system in combination with the BIM model can create the initial static 3D environment map. Accurate placement of QR code markers in the model ensures precise registration and tracking. Subsequently, real-time data is collected from video streams captured by CCTV cameras placed strategically in the environment. A data integration and processing layer includes both the alignment and DR processing modules. In this layer, the aligned BIM model is integrated with the real-time observation data from the CCTV cameras. Through this integration, the dynamic updating of the DR visualization is achieved, ensuring a seamless and accurate representation of the background scene. The last layer involves the visualization of the enhanced scene in a MR environment. In our implementation, a Microsoft HoloLens 2 headset was utilized to present the MR visualization to the crane operators, allowing them to perceive the virtual and physical elements seamlessly. The visualization module provided the crane operator with an enhanced and contextually accurate representation of the construction site. The headset's advanced hand and gesture recognition capabilities enabled precise and responsive interaction with the MR environment. Crane operators could easily manipulate and navigate the virtual content using natural hand gestures, allowing for efficient and fluid control over the DR visualization.

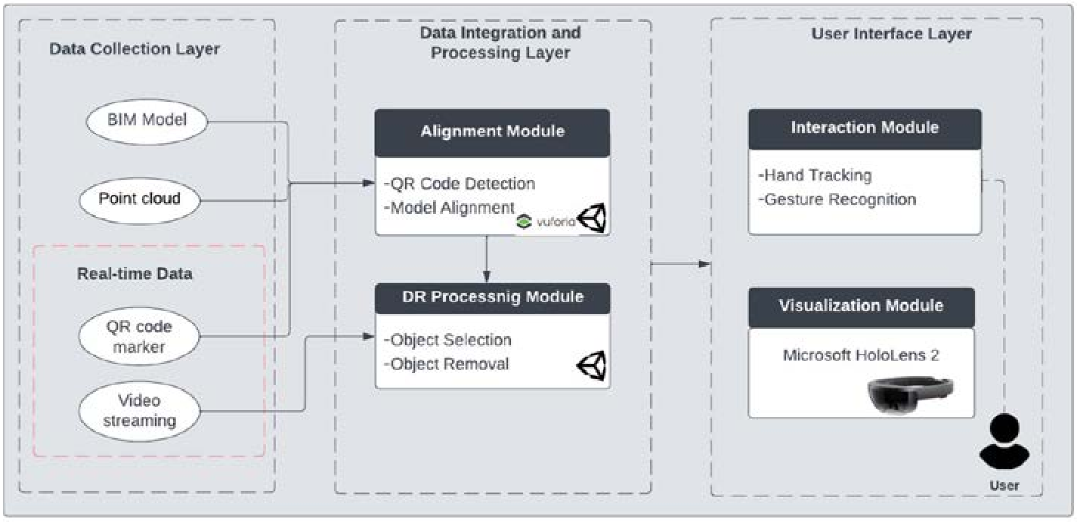


Fig. 2. System architecture for enhancing crane operator visibility

The system is implemented using C# programming in the Unity 3D environment. Unity 3D facilitates integration of video streams into a virtual environment. The OpenCV framework is employed to execute real-time image processing algorithms on the frames, enabling efficient and responsive operations. Additionally, a Wi-Fi connection is established between the HMD (Head Mounted Display) and the CCTV cameras. This wireless network connection allows seamless video streaming to the HMD, ensuring real-time visualization of the environment.

Fig. 3 shows the process flow of the generated prototype system, which will be elaborated in the following subsections.

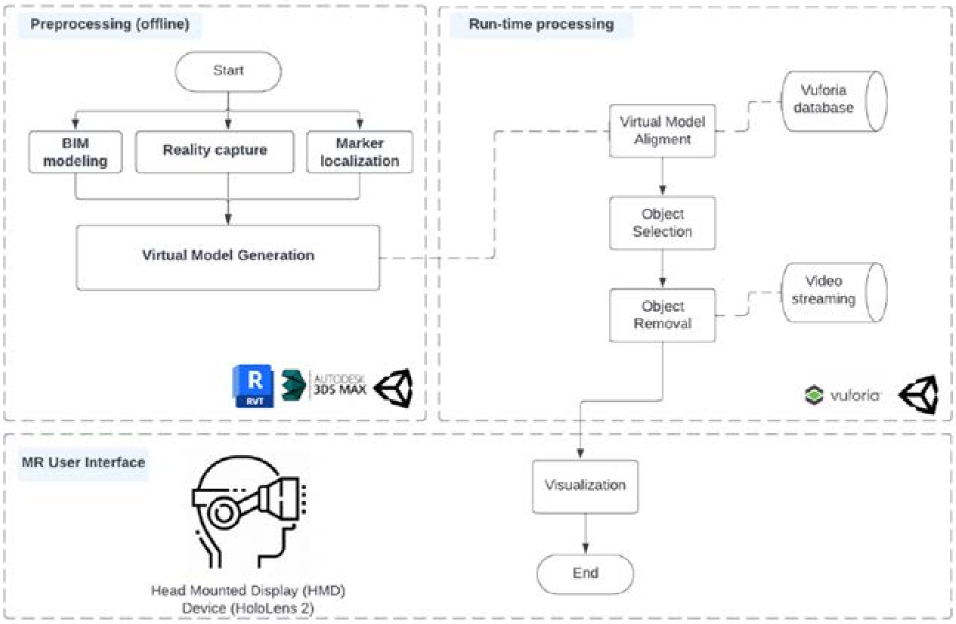


Fig. 3. DR process flow

3.1 Virtual Model Generation

First, the virtual model of the environment is generated using the BIM model in combination with reality capture techniques. The 3D scanner plays a vital role in reality capture by providing highly accurate and precise point clouds of the environment. It captures intricate details and geometries, ensuring that the virtual model is an accurate representation of the real-world site. Compared to the Structure from Motion (SfM) method (utilized in (Inoue et al., 2018)), which heavily relies on the quality and number of images taken to reconstruct the background, the 3D scanner captures data directly from the environment, minimizing the dependency on photo quality and providing a more robust solution. Furthermore, accurate scene reconstruction can be highly challenging when applying the SfM method to complex construction environments. The 3D scanner, with its high precision, can handle such complex environments more effectively, leading to a more reliable and detailed background generation. Then, Autodesk 3ds Max is used to create a high-quality 3D model of the scene using the BIM model and point cloud data. This 3D virtual model can then be optimized and converted into a low-polygon model suitable for real-time rendering in game engine environments. In addition, the location of the QR code is defined in the virtual model in this step for the marker-based registration. The physical QR code marker is subsequently placed in the correct location within the environment.

3.2 Virtual Model Alignment

As indicated in the previous subsection, to adequately align the virtual model in the physical world, QR code markers are used. A Microsoft HoloLens 2 headset tracks the camera's position, ensuring accurate alignment of the virtual and physical scenes. Vuforia image target technology (Vuforia Enterprise Augmented Reality (AR) Software | PTC) plays a crucial role in achieving precise alignment between the virtual and physical scenes in this study. As the user scans the QR code marker using a headset equipped with the Vuforia engine, the system identifies the unique image target and establishes a reference point. By recognizing the image target (the QR code marker stored in the Vuforia database), Microsoft HoloLens gains an understanding of its position and orientation in the real-world environment.

3.3 Object Selection

Users can interact with the virtual model by selecting objects they wish to remove from their view. Upon selection, information about the object, including its metadata transferred from the IFC model, is displayed in the user's view. This interactive process allows for a more user-friendly and intuitive experience.

3.4 Object Removal

The process of object removal involves several steps in an MR environment. First, the system captures real-time video streams from CCTV cameras, which provide a view of the target environment, including obstructive objects. Using the interactive HoloLens interface, the operator can select a region of interest, which includes obstructive objects like walls. The frames captured by the CCTV camera are transmitted in real-time, accompanied by annotation information, including the camera's pose at the time of each frame. After any distortions are repaired, these frames are decoded and uploaded as textures to the GPU (Graphics Processing Unit) of the headset device, enabling the generation of a DR view. The image warping process is then initiated, identifying corresponding points between the selected region in the operator's view and the frames coming from the real-time video stream. By calculating a transformation matrix based on these points, the system precisely aligns the background view with the real-world environment from the crane operator's perspective. As a result, the selected obstructive objects are visually replaced with the corresponding background from the virtual model. The HoloLens application renders this augmented view, providing the crane operator with an unobstructed and clear representation of the environment. The entire process happens in real time, updating when the crane operator moves or changes their perspective, resulting in better awareness of the situation and informed decision-making during complex lifting operations.

3.5 Visualization

The final MR visualization, presented through the headset, seamlessly combines real-world observation data from CCTV cameras with the DR-processed view. Obstructive objects, previously removed using image warping, are no longer present in the operator's field of view, ensuring an unobstructed and clear perspective. This MR visualization empowers the crane operator with real-time and accurate information.

4. CASE STUDY

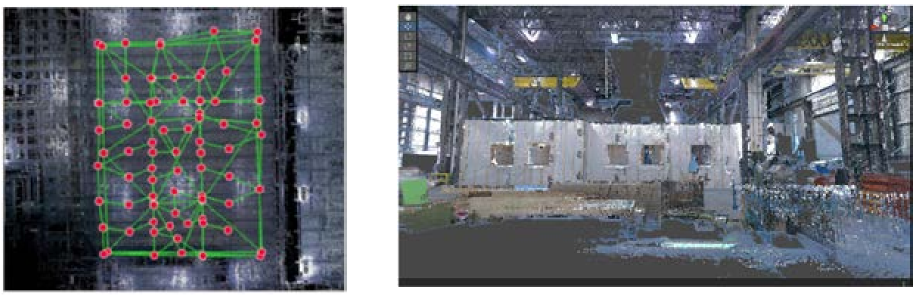
In this case study, we conducted initial steps for the validation of our developed system in a real-world setting at a prefabrication factory's shop floor located in Montreal, Canada. The manufacturing of prefabricated modules is done on the factory’s production floor, with distinct zones and the presence of cranes for material handling (see

Fig. 4 (a)). The type of crane used in this study is an overhead crane, which is defined by its ability to move along rails that are located overhead, thereby offering flexibility in the lifting and handling of material. The system's capabilities in improving operator visibility and safety during crane operations are the focus of this case study. The crane operator is equipped with a remote controller to manipulate the crane's movements and operations. The modules are placed in close proximity on the shop floor due to a lack of space. The operator's viewpoint is obstructed by this setup, which reduces their ability to see crucial parts such as the hook of the crane. In these situations, the operator requires the presence of additional workers near the hook to help manage the entire operation. The integration of the overhead crane with the proposed BIM-based DR system provides a solution to overcome the challenges of limited visibility faced by crane operators. As shown in Fig. 4 (c), the CCTV cameras were strategically placed around the module. Fig. 4 (b) shows the 3D virtual model of the prefabricated module.

(a) (b) (c)

Fig. 4. Experimental area; (a) Physical factory environment, (b) Virtual model of one module, and (c) Factory and camera settings in Unity environment.

Point clouds of the environment are collected by Leica Cyclone REGISTER 360, as illustrated in Fig. 5 (a), (b). The point cloud in combination with BIM model helps us to generate a low-polygon virtual model of the scene (shown in Fig. 4 (b)). The process began by placing a QR code marker at the same location in the physical scene as in the virtual model. When the crane operator wore the HoloLens and scanned the QR code marker, the HoloLens accurately tracked the camera's position and orientation, ensuring precise alignment between the virtual and physical scenes.



(a) (b)

Fig. 5. Point clouds of the environment collected by Leica Cyclone REGISTER 360; (a) Scanning stations; (b) Point cloud data of the target module.

Fig. 6 (b) illustrates the final result of the DR process within the HoloLens 2 environment through a screenshot of the user interface. In the screenshot, the actual prefabrication shop floor is displayed, and obstructive objects are highlighted as regions of interest. Crane operators can use the HoloLens 2's gesture recognition capabilities to select specific obstructive elements by drawing regions of interest around them using natural hand movements. Once the regions of interest are selected (red dash line in Fig. 6 (b)), the DR visualization algorithm processes the data in real-time to remove the obstructive objects from the operator's view.

Fig. 6 (a) shows the operator's view prior to the application of the DR process, providing as a reference point for the visual change affected by DR, as shown in Fig. 6 (b).

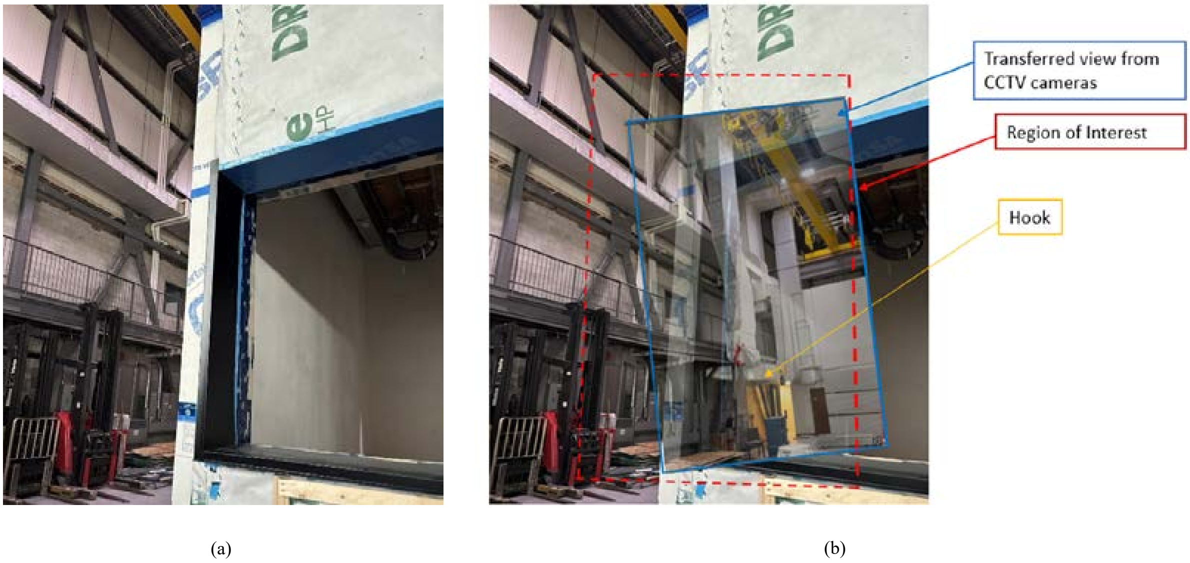


Fig. 6. HoloLens view, :(a) before the DR process; (b) after the DR process.

5. DISCUSSION

The application of BIM-based DR for enhancing crane operator visibility presents a promising solution for addressing challenges related to obstructed views in construction sites. The proposed system effectively combines advanced visualization technologies and real-time data integration to provide crane operators with a clearer and unobstructed view of their operational scene.
The integration of BIM data and real-time observation from CCTV cameras improves the DR visualization's accuracy. This integration tackles the issue of reliable background information by providing a continually updated view of the surroundings via real-time video streams. This ensures that crane operators are provided with a realistic and up-to-date representation of the construction area.

Despite the demonstrated effectiveness of the developed system, some limitations and challenges have been identified. The accuracy and reliability of the DR visualization heavily rely on the quality and availability of real-time observation data. In addition, factors such as changing lighting conditions and dynamic physical environment can influence the accuracy of tracking and registration. Future research can explore potential solutions, such as leveraging advanced imaging technologies or integrating cutting-edge technologies, including sensors and cloud solutions. For example, sensors such as LiDAR (Light Detection and Ranging) can be used to create detailed 3D maps of the environment to help operators in navigating complex environments, detecting obstacles, and improving situational awareness. Position sensors, such as GPS (Global Positioning System), can precisely track the crane's location. Cloud solutions can also be used for data storage and accessibility, providing a centralised and secure repository for storing large amounts of sensor data such as photos, videos, and sensor readings. In addition, cloud-based analytics tools can process sensor data in real-time, providing valuable insights to crane operators. By overcoming these challenges, we can further enhance the precision and reliability of the system, opening up new possibilities for improved crane operator visibility and safety at construction sites.

6. CONCLUSION

This research investigated a BIM-based DR approach to enhance crane operator visibility and safety at construction sites. By dynamically removing obstructive objects in real-time, the proposed system offers crane operators an unobstructed view of the construction scene, significantly improving their visibility and decision-making. The seamless integration of BIM data and real-time observation data enables a realistic and accurate DR visualisation. While our developed system shows promising results, further investigation is needed to address limitations such as the quality of real-time observation data and challenges related to registration and tracking.

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ADAPTING BIM-BASED AR POSITIONING TECHNIQUES TO THE CONSTRUCTION SITE

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ABSTRACT: *While Building Information Modelling (BIM) can support the management and visualisation of construction projects, Augmented Reality (AR) holds great promise to enhance interaction with these complex models. The accurate positioning of BIM-AR models in construction sites is critical to ensure that the virtual and real-world environments are correctly aligned. Through a literature review, this paper presents a review of state-of-the-art positioning techniques. It explores the different techniques used to position BIM-AR models and understands the interconnections and differences between them, with an emphasis on their applicability to the construction industry. The review also explores the challenges and limitations of each technique, in terms of the trade-offs between accuracy, computational efficiency, and robustness in varying environments. By providing an overview of positioning techniques in BIM-AR, this paper aims to guide researchers and practitioners in assessing the suitability of these techniques in the context of construction sites. The insights gained from this review may inform the development of efficient BIM-AR platforms that are more aligned with the dynamic and complex nature of construction sites.*

KEYWORDS: *BIM, Augmented Reality, Positioning*

1. INTRODUCTION

The construction industry is constantly looking for innovations and new methods to improve collaboration and productivity (Schiavi et al., 2022). Building Information Modelling (BIM) is a recent innovation in information systems that has proven its value for the construction industry. Currently, the use of BIM is a common practice in the built environment (Amin & Abanda, 2019), although its use in the construction stage is limited (Nassereddine et al., 2022; Sidani et al., 2021). Recent advancements in immersive visualisation technologies have created new prospects for exploring the potential of site-based BIM settings. The research on immersive visualisation technologies such as Augmented Reality (AR) and Virtual Reality (VR) has been growing with the aim of improving collaboration, productivity, and output quality of construction projects (Schiavi et al., 2022). In particular, the integration between BIM and AR can bridge the gap between the site and the office by enabling access to the BIM models onsite (Schiavi et al., 2022; Sidani et al., 2021). The potential of BIM-based AR integration is attributed to the potential improvements in collaboration and onsite information retrieval and representation (Wang et al., 2014). However, the majority of studies tend to investigate general AR applications that do not depend on the utilisation of BIM. The implementation of BIM-AR depends on complex software architecture and sophisticated positioning techniques which are not necessarily needed in general AR applications (Amin et al., 2023). The focus on BIM-AR should provide a deeper understanding of the specific benefits and limitations of the technology in the context of the practical requirements of real-life situations.

In the context of BIM-AR in the construction stage, the accurate positioning of 3D models onsite remains a major challenge and remains one of the most active research subjects (Azuma et al., 2001; Servières et al., 2021; Van Krevelen & Poelman, 2010). Positioning refers to the system's ability to accurately localise and track the BIM model with the proper alignment, orientation, and elevation (Amin et al., 2023). Numerous studies have explored a multitude of positioning techniques, employing different hardware and software components (Nee & Ong, 2023). The choice of the suitable technique is usually driven by a trade-off between accuracy, computational efficiency, and the region of space in which the system should work properly (Rolland et al., 2001; Servières et al., 2021). To decide whether a specific positioning technique is more effective for a specific use case, it is important to have a global understanding of the enabling technologies of positioning. In addition, it is important to explore how the effective management of positioning BIM-AR models in construction sites can have implications on the existing responsibilities and skillset of existing BIM roles. Hence, we adopt a literature review to survey state-of-the-art positioning techniques in the construction stage and develop a better understanding of their uses and limitations in the context of construction sites.

The motivation is to gain a comprehensive overview of the various positioning techniques in BIM-AR to capture the nuances and interconnections between them. This should help better understand their uses and limitations in the context of the dynamic and complex nature of construction sites. Such an understanding should provide insights into the development of BIM-AR platforms that are tailored to meet the demands of such challenging environments.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Khalid Amin, Grant Mills, Duncan Wilson, Karim Farghaly, *Adapting BIM-Based AR Positioning Techniques to the Construction Site,* pp. 175-183, DOI 10.36253/979-12-215-0289-3.17

In addition, we discuss how the effective management of positioning BIM-AR models in construction sites requires revisiting the existing structure of BIM roles including prospects for new responsibilities and skillsets.

2. LITERATURE REVIEW

AR encompasses a wide range of positioning technologies and methods, each with its own set of intricacies and considerations. Capturing the subtle differences and interconnections of these techniques requires a global understanding of Computer Vision, sensor technologies, and algorithm development. Positional tracking systems can be grouped under Outside-In and Inside-Out (Gourlay & Held, 2017). Outside-In systems utilise external stationary sensors or cameras (trackers) to track feature points -such as light emitters- that are mounted or assembled into the tracked device (Gourlay & Held, 2017; Pustka et al., 2012). The main drawback of Outside-In systems is that the accuracy and stability of tracking are limited by the space the trackers can cover (Gourlay & Held, 2017). On the other hand, Inside-Out, the system uses the cameras and sensors that are assembled in the device to map the environment and estimate its local pose (Figure 1). It is believed that Inside-Out systems have an advantage over Outside-In in AR because the former requires less environmental setup and enables a more dynamic experience (Gourlay & Held, 2017). Inside-Out is the dominant positioning technique used in smartphones and modern AR headsets. However, grouping positioning techniques of AR into inside-out and outside-in only partially describes the vast pool of approaches, hardware and software components used. It is more common to group AR positioning techniques under three categories based on the type of sensors: sensor-based, vision-based and hybrid (Amin et al., 2023). This classification is adopted by others (Rolland et al., 2001; Zhou et al., 2008), however, positioning techniques need to be understood with a wider BIM-AR function focus (Amin et al., 2023). Williams et al. (2014) provide an important application case study, which we update and extend in this study. This study expands on the systematic literature review in Amin et al. (2023) to develop and update a comprehensive map of BIM-AR positioning techniques in the construction stage. We provide a detailed description of each category and develop an understanding of the interconnections and differences between them in the context of the nature and requirements of construction sites.

Figure 1 Inside-out systems rely on a group of cameras and/or sensors manufactured into the headsets. These systems do not depend on any external sensory information.

3. RESULTS

3.1 BIM-AR Positioning Techniques

Regardless of the selected technique, any BIM-AR positioning system will need to do two tasks: estimate the local pose (location and orientation) of the user and construct a map of the surrounding environment (Wang et al., 2014). This happens through a two-stage process: a learning stage and a tracking stage. The learning stage comprises understanding the surrounding environment and recognising its features to create a spatial map that serves as a foundation for accurate tracking (Nee & Ong, 2023). The tracking stage is where the system initialises the coordinate system, localises the model in six degrees of freedom (6DOF), and monitors the changes to its location and orientation relative to the environment (Choi & Park, 2021; Zhou et al., 2008). To achieve accurate positioning of BIM-AR models, many techniques and approaches have been developed. Positioning techniques in BIM-AR can be grouped under three categories: sensor-based, vision-based and hybrid (Azuma et al., 2001; Billinghurst et al., 2015; Palmarini et al., 2018; Servières et al., 2021). Manual mapping is an additional technique that is not frequently mentioned in the literature due to its limitations (Amin et al., 2023). The dependency map in Figure 3 shows the different positioning techniques used in BIM-AR and the interconnections among them. The next subsections discuss how the technology works in each category in detail and describe the associated techniques and their limitations.

3.1.1 Sensor-based systems

Sensor-based tracking refers to the process of determining the position and orientation of a user or device within a real-world environment by utilizing various sensors (Rolland et al., 2001, Williams et al., 2014). Compared to vision-based tracking methods, sensor-based tracking is faster and more robust in determining the pose of the device, however, they are analogous to open-loop systems whose output could accumulate errors (Zhou et al., 2008). Several types of sensors are commonly used in sensor-based tracking in BIM-AR:

1. Inertial Sensors: Inertial sensors are commonly used in tracking systems for BIM-AR, usually as complementary sensors to visual ones. The most common inertial sensor used for pose estimation is Inertial Measurement Unit (IMU) (Nee and Ong, 2023). IMUs can provide accurate information for all six degrees of freedom about the pose of the device, usually by fusing information from integrated gyroscope, accelerometer and magnetometer (Ahmad et al., 2013). While inertial sensors provide high accuracy in short-term tracking, they suffer from error accumulation over time and need to be combined with other sensors for accurate tracking (Rolland et al., 2001, Williams et al., 2014, Nee and Ong, 2023). IMUs have become an essential component in all smartphones and modern AR headsets.

2. Laser-based Depth Sensors: also referred to as optical sensors, utilise different kinds of light in the infrared spectrum to measure depth information to understand the geometry of objects and surfaces in real-time, also known as depth sensors. Among several types of depth sensors, the Time-of-Flight (ToF) and Light Detection and Ranging (LiDAR) are the most commonly used techniques in BIM-AR (Amin et al., 2023). A ToF laser sensor emits an infrared laser beam and measures the time it takes to reflect back to measure the distance to an object (Rolland et al., 2001, Williams et al., 2014). LiDAR scanners are usually more expensive because they can cover larger areas and provide higher accuracy.

3. GPS: is a widely used sensor for outdoor localization. It leverages a network of satellites to determine the latitude, longitude, and sometimes altitude of a device. GPS enables location-based AR where digital elements are superimposed based on where the user stands as in Williams et al. (2014). Very few studies have utilised GPS to position BIM-AR models (Fenais et al., 2018; Williams et al., 2014) due to its low accuracy and low performance indoors.

4. Wireless Network Sensing: such as Wi-Fi or Bluetooth. They can be utilised for determining the location of the device but have significant limitations related to setup, coverage and accuracy (Craig, 2013, Williams et al., 2014). A single study utilised Wi-Fi for BIM-AR positioning (Degani et al., 2019).

Other sensors that are frequently mentioned in general AR literature but are not used in BIM-AR in the construction stage are magnetic sensors and acoustic sensors. Magnetic Sensors, also known as magnetometers, detect changes in the Earth's magnetic field to determine the orientation of the device. Due to the existence of magnetic fields apart from the earth's soft iron effect and temperature changes, magnetometers are highly susceptible to magnetic disturbances. As a result, their use is often disregarded in various applications, particularly in industrial settings as construction projects (Rolland et al., 2001, Nee and Ong, 2023). Acoustic Sensors utilise the principle of ToF used in optical sensors but use sound waves instead of laser beams. The speed of sound varies with environmental conditions and sound waves can be easily obstructed, so acoustic sensors are not a reliable tracking technique (Rolland et al., 2001, Nee and Ong, 2023). It is argued that the sole reliance on sensor-based techniques would introduce significant error variables (Craig, 2013). This is due to some requirements that are not always available on construction sites such as network coverage, and due to their sensitivity to some environmental conditions such as temperature, humidity, and noise. In addition, measurement errors are accumulated over time and need continuous calibration because pose estimation is evaluated based on the previous position (Craig, 2013).

3.1.2 Vision-based systems

Vision-based techniques rely on different computer vision methods to locate and track targets within a video sequence or a series of images (Jinyu et al., 2019; Servières et al., 2021; Williams et al., 2014; Zhou et al., 2008). A major advantage of vision-based techniques is that they rely on cameras which provide an affordable solution to capture lots of information, in addition to being available in many forms and types (Song & Kook, 2022; Yang et al., 2023). Vision-based tracking techniques use image processing methods to estimate the pose of the camera relative to the real world and so are analogous to closed-loop systems which correct errors dynamically (Zhou et al., 2008). However, they suffer at higher movement speeds and are dependent on the uncontrolled condition of the environment they are operating in such as scene complexity, lighting, and weather (Servières et al., 2021; Yu et al., 2016; Zhou et al., 2008). In addition, because vision-based techniques rely on recognising and tracking visual cues within the surroundings, it becomes challenging in an unknown environment as the system takes more time to collect enough data to analyse the surroundings to deduce the user's pose (Servières et al., 2021; Siltanen, 2012). To overcome this challenge, predefined signs (markers) that are easily detectable by the visual tracking system can be placed in the environment. This approach is called marker-based, where the marker is used as the reference for the positioning system to superimpose the virtual objects onto the real world (Nee & Ong, 2023; Siltanen, 2012; Williams et al., 2014). However, a major drawback of marker-based techniques is that tracking requires the markers to be always visible in the coverage area of the camera for a stable experience (Nee & Ong, 2023). A multi-marker tracking method that involves distributing a group of markers for the camera to detect to expand the coverage area has been developed. Yet, marker-based approaches are generally considered obtrusive and can be easily obstructed in construction sites (Song & Kook, 2022; Wang et al., 2013).

To overcome the limitations of marker-based tracking, markerless tracking can recognise and track natural features in the environment such as edges, corners, and textures, and use them as location references to overlay virtual elements and determine the pose of the user (Nee & Ong, 2023; Servières et al., 2021; Siltanen, 2012). Markerless tracking offers several advantages, such as flexibility and ease of use since it doesn't require physical markers. However, because the term "marker-based" implies the need to do some preparations in the environment before initialising the coordinate system, the term "markerless" implies a misleading perception that it can work anywhere without previous preparations. Globally, markerless tracking is often perceived as a universally capable technology, however, its practical implementation presents numerous challenges in terms of computational requirements, noise reduction, and user-friendly interaction techniques (Servières et al., 2021). The majority of research in BIM-AR adopts either a marker-based or a markerless approach, overlooking "extended tracking" approaches which allow tracking of digital elements to persist in the user's field of view even when the initial target is no longer in the frame of the camera (Vuforia.Com, 2023; Wikitude, 2023)

Differences among vision-based techniques can then be divided into model-based and Visual SLAM (Simultaneous Localisation and Mapping), also referred to as V-SLAM (Figure 3). While both techniques depend on feature tracking and matching between a series of images, the difference mainly lies in the system's knowledge of what it should track. Model-based systems use pre-existing information about the environment. In other words, the system has prior knowledge of what it will track which can be fiducial 2D features such as images and QR codes (marker-based approach), or a group of edges, corners, and textures that define a 3D object (object tracking approach) (Palmarini et al., 2018; Siltanen, 2012). In contrast, V-SLAM systems gradually reconstruct their environment while tracking the user's pose (Nee & Ong, 2023; Yang et al., 2023). V-SLAM techniques do not have prior knowledge of what to track, and so they continuously create information about surroundings utilising an "ad-hoc" visual tracking method (Palmarini et al., 2018; Servières et al., 2021). V-SLAM relies on principles from "Structure from Motion" (SfM) to create a 3D structure of an unknown environment and then expands by incorporating the aspect of real-time pose estimation through a set of algorithms that optimise computational efficiency (Nee & Ong, 2023; Yang et al., 2013). However, because the environment map is required for the pose estimation and vice versa the main challenge of V-SLAM approaches is the accumulation of small errors in the estimated poses which can lead to larger errors in the map information, etc. The development of hybrid systems, that fuse different kinds of sensory information, was designed to create more accurate results.

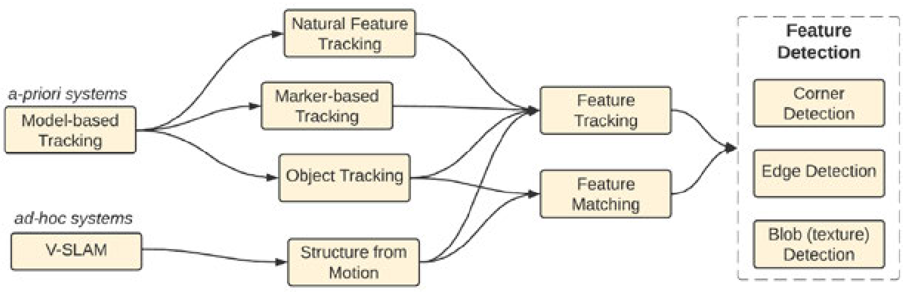

Figure 2 Interconnections between vision-based positioning techniques

3.1.3 Hybrid systems

Hybrid systems fuse information from different sensors and cameras to compensate for the limitations of each technique. In particular, the fusion of visual tracking systems and inertial sensors has gained significant popularity. Cameras excel in providing precise measurements by leveraging visual feature matching and multi-view geometry. However, in scenarios where image quality is compromised due to factors like rapid motion or sudden changes in lighting, purely visual tracking systems often encounter failures (Nee & Ong, 2023; Williams et al., 2014). In contrast, inertial sensors remain unaffected by image quality issues and demonstrate particular proficiency in tracking high-frequency, fast motion. Nevertheless, the measurements obtained from an IMU are subject to high noise levels and drift over time (Nee & Ong, 2023; Zhou et al., 2008). By fusing visual information from cameras and inertial information from IMUs, the system is more able to dynamically correct errors and provide more accurate results in constructing a 3D map of the environment while estimating the pose of the device. This is known as Visual-Inertial SLAM (VI-SLAM) which is the technology used for fusing the information from the different sensors for environment mapping and 3D pose estimation (Jinyu et al., 2019). VI-SLAM can be considered a subset of multi-sensor fusion techniques. Multi-sensor fusion is a broader concept that encompasses the integration of data from multiple sensors, which can include cameras, inertial sensors, GPS, LiDAR and more (Figure 3). Challenging aspects in hybrid systems are the need to perform calibration between the cameras and sensors to ensure that their measurements are aligned within a shared coordinate system, a process commonly referred to as hand-eye calibration (Nee & Ong, 2023).

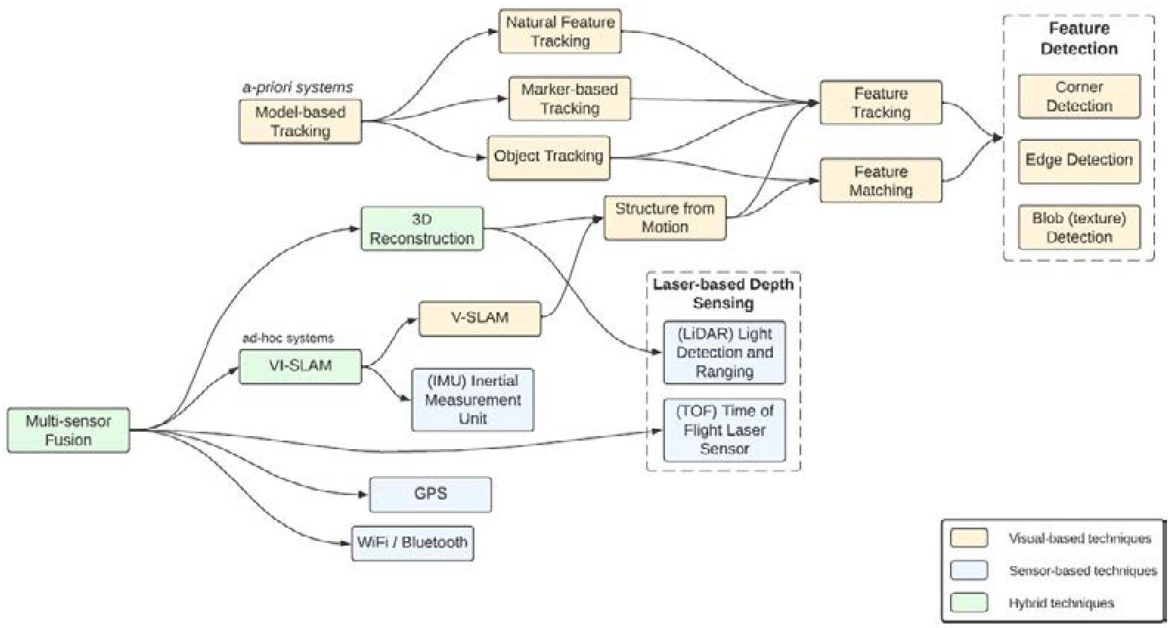

Figure 3 A comprehensive map of the positioning techniques used in BIM-based AR

3.1.4 Manual Mapping

To minimise the complexity of the dynamic real-time update of user movement relative to the surrounding environment, some studies used manual mapping techniques. Manual mapping involves using matrices to create a relation between world space and camera space and use this relation to overlay digital elements on physical objects (Amin et al., 2023). The world space represents the coordinate system that corresponds to the physical environment where objects have specific positions and orientations. On the other hand, the camera space refers to the coordinate system of the camera within an AR device which captures the real-world scene (Figure 4). By creating a similar situation using a virtual camera and a 3D model, the positioning system is then able to properly overlay and align digital elements from the 3D model by converting the coordinates from the world space to the camera space (Amin et al., 2023; Nee & Ong, 2023). Manual mapping techniques do not provide a dynamic experience as the user is restricted by the location of the camera. Few studies have experimented with this technique as in Dai and Lu (2010), Lin et al. (2020) and Gomez-Jauregui et al. (2019).

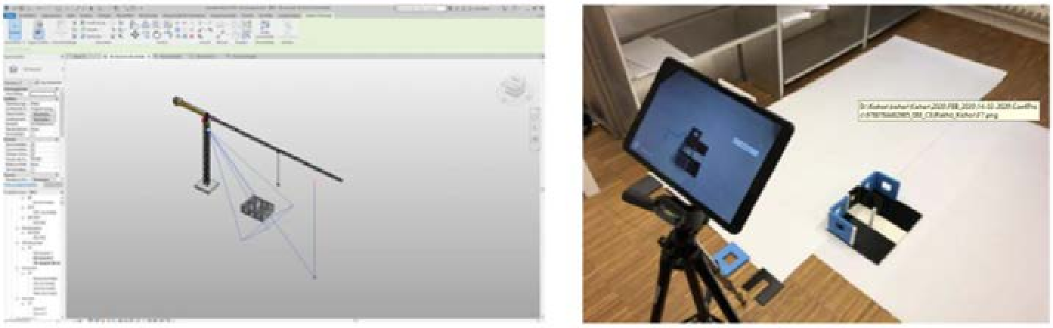

Figure 4 Demonstration of the concept of manual mapping from Lin et al. (2020)

3.2 Dominant techniques and devices

BIM-AR is used for four main applications in the construction stage: site assistance, construction planning, progress tracking, and inspection. Figure 5 shows the techniques used in the mentioned applications. Various methods and techniques are used across applications with the exception of LiDAR. And so, the development of BIM-AR platforms that are capable of supporting different positioning techniques may be required. In addition, more research is needed on the effectiveness of these techniques from a practitioner perspective. While several studies have been carried out in real-world construction sites, the focus has been on the technological aspects of BIM-AR not on the practical implementation of the technology.

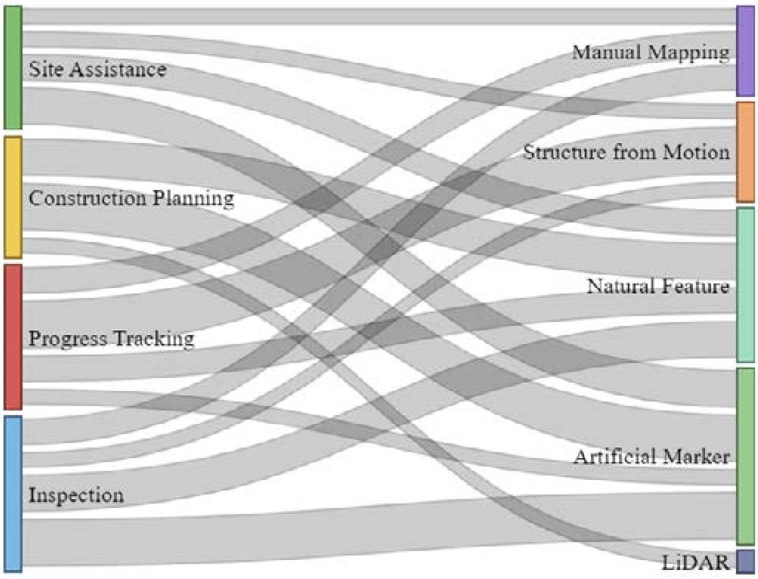

Figure 5 Positioning techniques used in different construction applications

4. DISCUSSION

Common in BIM-AR positioning is the need to map anchor points between digital models and the physical environment. The positioning system will always require a physical reference in the real world that can be mapped to a reference in the digital model. In BIM-AR applications that utilise natural features for positioning, users are usually asked to select a vertical wall edge and a horizontal edge representing a horizontal direction, then select the corresponding edges in the digital model. The same process occurs with artificial markers; the locations of the physical markers are mapped to digital ones in the digital mode. The dynamic nature of construction sites requires that the locations of these anchor points will perhaps change frequently as the project progresses. Studies that used marker-based indicated that in the context of construction sites, there is a considerable possibility that markers will get obstructed by other objects (Kwon et al., 2014; Lin et al., 2020). Studies that used natural feature tracking have argued that they could be obstructed due to other construction activities or disappear because site scenes keep changing (Lin et al., 2019; Mirshokraei et al., 2019). It is critical therefore to understand how construction activities unfold and assess the accessibility of reference physical elements before selecting the most suitable positioning approach. The locations of anchor points need to be coordinated and updated accordingly to ensure continuous alignment between the BIM model and the evolving site conditions.

The continuous coordination of anchor points between the physical site and the digital model necessitates revisiting the responsibilities of existing BIM roles. Existing BIM roles are usually oriented around generating and managing information across different stakeholders for design activities. We envision that a new responsibility will emerge to manage the accurate positioning of BIM-AR models onsite. This new responsibility, dedicated to BIM-AR coordination, will coordinate the anchor points between the site and the digital model and manage the communication with site personnel and their safety. Therefore, more collaboration between BIM and site professionals is needed to consider factors such as site constraints, logistics, and project stages. Adapting BIM-AR positioning techniques to the nature of construction sites is a crucial step in leveraging the technology. In addition, it is necessary to revisit the skills of BIM roles and workforce training programmes in the context of BIM-AR requirements.

5. CONCLUSION

We have provided insights into the positioning techniques used in BIM-based AR for construction projects. By exploring the different positioning techniques used in BIM-AR, their interconnections, and their differences, this study aimed to provide insights to researchers and practitioners for assessing the suitability of these techniques in a construction site context. The results of the review identified three main categories of positioning techniques: sensor-based, vision-based, and hybrid systems. Sensor-based systems utilise various sensors like IMUs, laser-based depth sensors, and GPS to track the position and orientation of the device. Vision-based techniques rely on computer vision methods and can be further categorised into model-based and V-SLAM approaches. Hybrid systems combine information from different sensors and cameras to compensate for the limitations of individual techniques. VI-SLAM is the core technology of multiple-sensor fusion. Additionally, manual mapping techniques were discussed, although they are not commonly used due to their limited dynamic capabilities. The review highlighted the challenges and limitations of each technique, such as accuracy, computational efficiency, and robustness in varying environments. It became noticeable that the choice of positioning technique depends on the specific requirements of construction applications, and there is no one-size-fits-all solution. Hence, we proposed guiding the research on BIM-AR to involve flexible positioning systems that can adopt more than one technique. In addition, the findings shed light on the need for continuous coordination of anchor points between the physical site and the digital model considering the evolving nature of construction sites. Consequently, a new responsibility, dedicated to BIM-AR coordination, will emerge to manage the positioning of BIM-AR models onsite and communicate with site personnel. This calls for more collaboration between BIM and site professionals, as well as revisiting the skills and training programs of existing BIM roles to accommodate BIM-AR requirements.

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SAFETY TRAINING FOR RIGGING USING VIRTUAL REALITY

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ABSTRACT: *Tower and Mobile Cranes are some of the most commonly used heavy equipment in all construction sites, and any crane failures could lead to significant human and monetary losses. Moreover, rigging configuration determination is a critical task that requires the rigging crew to have significant experience and knowledge of various failure modes that can be encountered when performing lifting operations. However, despite the criticality of training riggers, there has yet to be a comprehensive tool used to train and guide inexperienced riggers, and hence, more practical tools are needed. This paper proposes a framework for using Virtual reality (VR) and simulation to train riggers to identify the optimal rigging configurations based on the lift type and the external conditions. Through 3D modeling, the critical components of the rigging system are modeled to accurately simulate the rigging system and their performance when faced with critical loading scenarios. The developed framework is expected to allow inexperienced riggers to identify critical failure modes and enhance construction operations' overall safety performance and productivity. Furthermore, several scenarios are assessed based on historical evidence for rigging configuration failures, and the efficiency of the training tool is assessed through real-life scenarios and tests.*

KEYWORDS: *Crane Operations, Lift Planning, Rigging, Safety, Training, Virtual Reality.*

1. INTRODUCTION

Globally, construction and industry-related incidents account for significant human and material losses; as a result, the construction industry is considered one of the most hazardous industries for workers. According to the Occupational Safety and Health Administration (OSHA,2020), in 2019, 1061 worker fatalities occurred in the construction industry, accounting for 20% of deaths in all industries. A contributing factor to the increased number of incidents is the use of heavy pieces of equipment, where many fatal injuries were a result of using heavy equipment." For instance, in Australia, Safe Work Australia 2019 reported that there are, on average, 240 serious injury claims reported from crane safety incidents". Furthermore, the current construction trends, such as Off-Site construction (Lingard et al.,2021), are gaining more traction for project execution. Moreover, Off-site construction is heavily reliant on cranes, and thus, an increase in crane usage is inevitable. Fatal incidents would increase exponentially with the increased use of crane construction projects. Thus, it is critical to understand the underlying reasons for incidents related to crane operations and to develop the necessary tools required to mitigate the number of incidents.

Much research has been conducted to understand the causes of crane incidents. (Milazzo et al ,2016) Analyzed 937 crane incidents and identified that the leading cause of incidents for different cranes is overturning and collapse, mainly due to structural failures caused by overloading. Another contributing factor is human error (Milazzo et al., 2016) found that one-third of crane incidents were triggered by human error, resulting in either weight underestimation or improper operation of the crane. (Lingard et al.,2021) Identified that the main types of incidents in crane operations are those related to electrocutions and tip-over incidents. On one side, electrocution incidents result from improper planning, unsafe working conditions, and human negligence. On the other hand, Tip-over incidents are mainly caused by overloading, loss of center of gravity, and outrigger failure. Finally, (Tam and Fung,2011) identified four main factors causing safety incidents in crane operations: negligence and misjudgment, inadequate training, subcontracting, and pressure from deadlines. Thus, to mitigate crane-related on-site incidents, it is necessary to eliminate human error, avoid overloading and structural failures. (Zhang et al.,2023) the overturning and loss of center of gravity can be prevented by securing the lifted loads; this prevention is a major duty of rigging personnel whose performance can be enhanced through adequate training.

Training has been a primary focus for crane operations, where many tools were used to provide operators, riggers, and signalers with the proper procedure to perform lifts. In most cases, only traditional training methods were used, which centered around textbooks, video tutorials, and a limited amount of hands-on experience, which is less immersive. (Wu et al.,2020) argues that learning by doing has been recognized as a more effective training method. Furthermore, they argue that traditional lecturing courses are less effective in transmitting learning

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Rafik Lemouchi, Mohamed Assaf, Mohamed Al-Hussein, Khaoula Boutouhami, Ahmed Bouferguene, *Safety Training for Rigging Using Virtual Reality,* pp. 184-194, DOI 10.36253/979-12-215-0289-3.18

knowledge. Luckily, recently, with the rise of VR, more research is being conducted to understand the impact of VR training on construction workers. For instance, (Joshi et al., 2021) used VR technology for safety training in the precast/prestressed concrete industry and found that knowledge gained through traditional methods is lower than that gained from VR training methods. (Song et al.,2021) developed a VR crane operator training module and reported that VR training effectively enhances crane control skills competence.

Crane operations and VR training procedures are scarcely represented in the literature, where only a limited set of works were published regarding crane-related operations and VR training. Previous works focused on using VR to visualize crane lifts and hazard identification through clash detection. (Shringi et al.,2022) for instance, developed a hazard identification training model for crane operators, which focused mainly on tower cranes. (pooladvand et al, 2021) Used interactive VR to evaluate mobile crane lifts. While (Song et al, 2021) developed a VR crane operator training module but did not take into consideration the rigging personnel training. Regarding rigging, (Zhang et al., 2023) developed a collaborative training model for crane operators, riggers, and signallers. However, the main focus was on collaboration between the different project participants. Furthermore, for rigging, only a semi-immersive CAVE system was utilized for collaboration and communication between the different project participants taking part in operating, and guiding cranes. However, a training system which takes into consideration the elaborate and complex properties of rigging components is yet to be tackled by any work.

Thus, this work identifies the need for developing a fully immersive and engaging tool to train riggers and mitigate on-site incidents. To do so, the authors propose a fully immersive VR-based training framework for riggers to tackle the main causes of crane-related on-site incidents. The proposed methodology is expected to improve the overall safety of crane operations as well as decrease the number of incorrect assemblies and improving the overall performance of crane related operations.

2. METHODOLOGY

The overall methodology proposed by the authors is summarized in Figure 1.

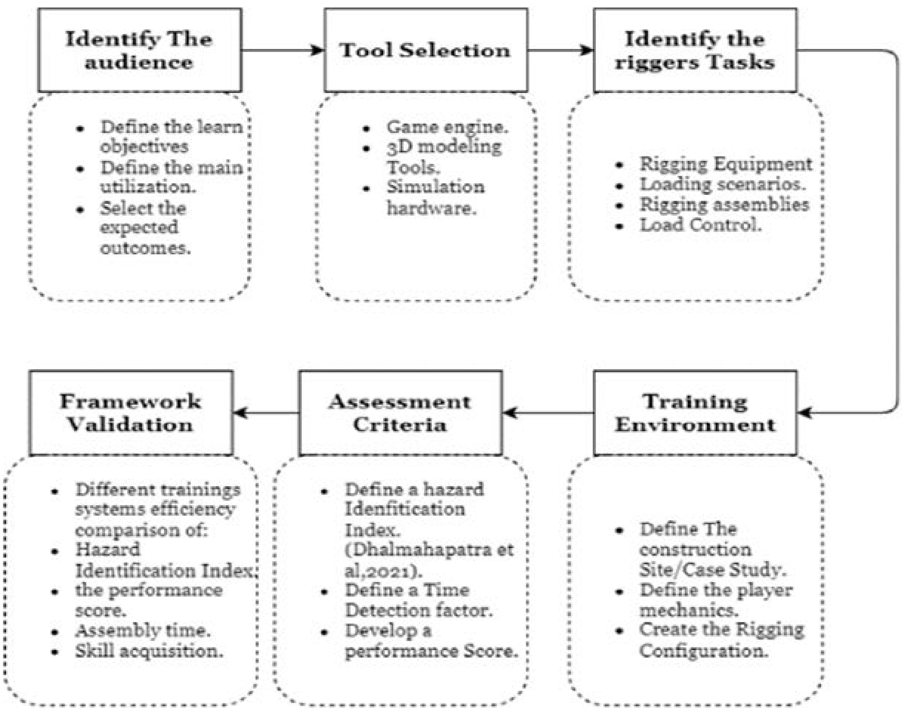

Fig. 1:Research Methodology

The initial step is to identify the audience of the VR tool. Later, tool selection is vital in any VR environment; a set of decisions are needed to select the game engine and the VR hardware to improve the overall experience. Next, the main issues encountered on-site are identified to enable the development of a realistic model capable of accurately representing the real working environment. Moreover, to assess the training progress, a set of assessment criteria is needed to estimate the trained personnel's overall performance objectively. The next step is to build the training environment by initially creating 3D models of the rigging components using 3DSMax and

SolidWorks. Then, to represent the construction site, a BIM model of a real project is exported to the VR environment, and a set of training scenarios are selected appropriately. Finally, a set of validation tools are implemented to validate the methodology, and the results are discussed.

2.1. Identify The Audience

The primary focus of this study is to utilize the Virtual Reality (VR) training tool to teach novice and inexperienced riggers the best practices for safe crane operations. The tool aims to enhance the overall safety of crane operations by addressing critical aspects such as better rigging assemblies, identification of erroneous assemblies, secure load lifting, and identification of faulty equipment. Additionally, civil engineering students seeking to learn crane operation concepts can also benefit from this tool.

2.1.1. Define the learning objectives.

The learning objectives of the training module are as follows:

- Enhancing skills in rigging assemblies: Trainees will learn how to select and assemble the appropriate slings, shackles, hooks, spreader bars, and bolts according to the specific load being lifted.
- Identifying and avoiding hazards: Trainees will be educated on identifying potential hazards during rigging operations and how to avoid accidents by adhering to safety guidelines such OSHA.
- Securing loads during lifting: Trainees will gain insights into load calculations, determining the center of gravity, and ensuring the load is securely balanced and lifted correctly.
- Detecting faulty equipment: Trainees will learn how to inspect rigging equipment prior to assembly and identify any faulty components that may compromise safety.

2.2. Tool Selection

To develop a fully functioning and accurate training module, it is first necessary to select the necessary tool to develop the module. The following sections will discuss the selected Game engine,3D modeling tools and the hardware used throughout this work, as well as the reasoning behind selecting these tools.

2.2.1 Game Engine and 3D modeling Tools

As for the game engine, Unity3D was selected due to its ease of implementation and the availability of a diverse set of libraries and tools which can be used for simulation purposes. The 3D modeling software selected are 3DS max, and SolidWorks.3DSMax was used to import and design some of the necessary components of the raining environment. While SolidWorks was used to create 3D models for the rigging components, such as the hooks, spread bars, slings, and eyebolts. Both 3D software were also chosen since they are compatible with the selected game engines, where it is advisable to use the previously mentioned software alongside a rendering software to provide a more realistic and engaging training environment.

2.2.2 Hardware Description

As for the hardware, an HTC Vive Headset was used for training. The headset was used to allow the user to explore the environment. two Wireless controllers were also used, their utility lies in allowing the user to move through the environment and interact (grab, assemble and dissemble) the relevant rigging components. The movement of the player was detected using two HTC bases. The overall system was run on a supercomputer, with an I9 CPU, and NVIDIA RTX A2000 GPU and 32Gb of RAM.

2.3. Rigger Tasks

After thorough analysis of crane operators training guides such as (ATP 2013), as well as analyzing relevant research such as (Zhang et al, 2023) works riggers tasks were identified as follows:

- check the rigging equipment, in other words, select the appropriate slings, shackles, hooks, spreader bars and bolts in accordance with the module to be lifted.
- load calculations, and center of gravity determination of the loads to be lifted.
- Rigging equipment inspection prior to assembly.
- rigging assembly, by ensuring that each component is secured and respects the angular limits.

- Load Control by ensuring the load is balanced and lifted properly throughout the lift. Ensure the center of gravity and hook are aligned.

2.4. Training Environment

In order to accurately model a construction site, and its properties. The Unity3D engine is used to develop a realistic construction site as well as the user interaction with said environment. The following section will delve into detail and discuss both the construction site and the human interaction within the environment.

2.4.1 Construction Site and Rigging Configuration

A virtual construction site was created to provide the trainees with a sense of dimensions and realism when training which can be seen in Figure 2. The site is populated with various interactable items similar to a real construction site. The rigging components and other items in the virtual training environment are modeled on 3D software with accurate dimensions and physical properties to those used in real operations. However, the interactable items the trainees can interact with, and use are mainly those required to assemble a rigging system. Additional components that are either faulty or unneeded are added to render the tasks more challenging and, eventually, more rewarding. Furthermore, to enhance immersion, audio, and interactive interfaces were used to imitate a real-life learning environment and provide an optimized training process.

Fig. 2: Training Environment.

2.4.2 VR Controls

Replicating human interaction in a virtual environment is often a complex task, specifically when the Virtual environment is large in scale. The main difficulty encountered is regarding the locomotion system which is related to the ability to roam and use to environment.to tackle this issue, two different systems of movement are used to replicate the movement of workers on site. The first system, which is generally used in serious desktop based serious games where the user inputs the direction continuously through a touchpad. The second system is through a teleportation system, where the user can teleport to any accessible location in the construction site. The user is given the option to use one or a mixture of the systems according to their preferences. However, it is preferable to use the second system if the user is more likely to encounter VR dizziness.

As for the interaction system, the user can grab, assess, assemble, and disassemble any rigging components, which is the main feature used to create a realistic interactive training system. Finally, after assembling the rigging, the user can evaluate the efficiency and accuracy of their assembly by performing a lift. The lift is subjected to the environmental conditions present in a construction site, which are accurately replicated in the Unity environment.

2.5. Assessment Criteria

In order to assess the performance of the participants and the efficiency of their training, a hazard identification index inspired by (Dhal Mahapatra et al,2021) is used to grade and measure their performance. The scoring system identifies the primary and secondary tasks to be executed by the participant. Each task is given a score ranging from a one to three scale where one is a basic task that is fundamental but is not critical to the overall safety, and 3 is an advanced task critical to ensuring crane operations. The score system is also affected by a time factor or a time detection factor to put an emphasis on completing the tasks within the allotted time. Table 1 illustrates the different training levels and their assessment criteria.

Table 1: Training Assessment Criteria for different.

Level	Task Description	Score Range
Level 1 - Basic Task:	Fundamental actions and responsibilities contributing to the safety and smooth functioning of crane operations. These tasks require moderate skill and understanding but are not considered critical or highly complex.	1-3
Level 2 - Intermediate Task	Moderately complex actions that are more crucial to the overall safety and efficiency of the crane operations. These tasks require a higher level of skill, attention to detail, and decision-making.	4 to 7
Level 3 - Advanced Task	Critical to ensuring crane operations' utmost safety, accuracy, and effectiveness. It involves handling challenging scenarios and potential emergencies and making critical decisions promptly. These tasks demand a high level of expertise, problem-solving abilities, situational awareness and timely decision making.	8 to 10

2.6. Framework Validation

(Harris et al, 2020) defined validation as the extent to which a test, model, measurement, simulation, or other reproduction provides an accurate representation of its real life equivalent. Furthermore, (Salinas et al, 2022), defined evaluation methods as either objective or subjective.

2.6.1 Objective methods

Objective methods are those methods which evaluate efficiency based on factual data. (Salinas et al, 2022) found four main objective methods used in literature. For safety training, they are defined as follows:

- safety improvement: by comparing the behavior under training with the recommended behavior defined by safety requirements.
- performance time: measuring the time needed by a trainee to preform the required tasks, while also considering the impact of making a wrong decision. This method is used to measure the consequences of timely decision making on the overall on-site safety.
- number of errors measures the number of errors committed by the participants. And for this case study, compare the results for different groups of participants to gain a deeper understanding the VR tools impact on decreasing the number of errors made.
- measurement of vital signs: based on monitoring vital sings of trainees to understand the physical and psychological impact of stressful and dangerous scenarios on the overall performance of the trainees.

2.6.2 Subjective methods

Subjective methods are those methods which evaluate efficiency based on the trainees' feelings and preferences. (Salinas et al, 2022) mentions 4 major subjective evaluation methods which are sensory user emotions, expert analysis, user field workload and interviews and questionnaires.

Thus, and in order to validate the proposed framework, different validation techniques are used in the initial trials, both objective and subjective. As for objective methods, two validation techniques were deemed appropriate, which are performance time and number of errors, these two methods were selected to measure the learning of the trainees as well as understand the impact of timely decision making on the overall performance of crane operations. The rest of the objective methods were not used for this work; However, the developed model allows the inclusion of these methods in future studies.as for subjective methods, questionnaires and interview were used to validate the overall experience the users had when interacting with the training environment.

3. MODEL DEVELOPMENT AND TRAINING PROCEDURE

When developing the training procedure, a natural progression from more manageable tasks to more complex tasks was selected to increase the efficiency of the overall training. The training procedure was inspired by relevant training manuals such as the ATP 2013 and crane safety-related standards. The training consists of four primary levels, starting from a basic introduction to the crane safety problem. Then, a components identification module for rigging assemblies, followed by a basic assembly and secure rigging module. The training procedure is finalized with an advanced assembly and simulation concluding module. The four are explained in more detail below.

3.1 Basics Introduction

Briefly explain the importance of proper crane rigging techniques and the potential risks associated with incorrect rigging. Emphasize the need for a comprehensive training program to ensure safe and efficient rigging operations. A sample of the GUI is shown in Figure 2.

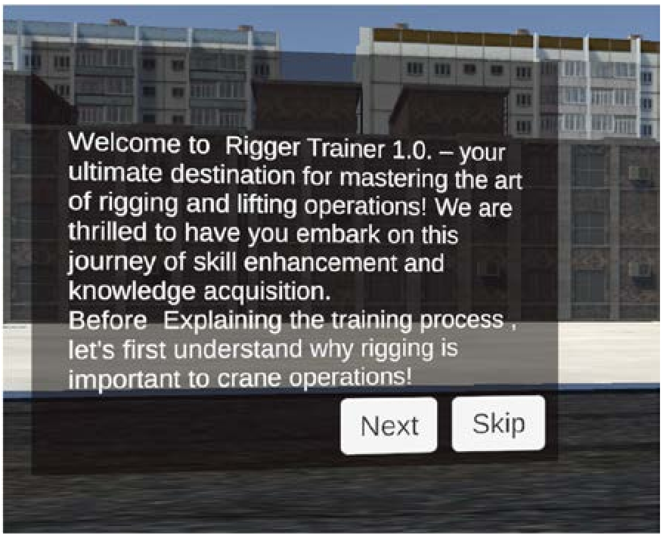

Fig. 3: The Introduction GUI.

3.2 Level 1 - Component Identification

At the outset of the VR training program, we prioritize establishing a strong foundation for trainees by focusing on providing a comprehensive understanding of the fundamental components that make up a rigging system. Through engaging 3D models and interactive hands-on exercises within the virtual environment, participants will delve into the intricacies of identifying key elements such as slings, shackles, hooks, and spreader bars. The VR experience offers a realistic and immersive environment, allowing trainees to explore lifelike representations of these vital components. By interacting with the 3D models, they will gain invaluable insights into the unique features and applications of each component. This in-depth comprehension is critical for ensuring safe and effective rigging practices in real-world scenarios. As trainees virtually manipulate the slings, shackles, hooks, and spreader bars, they will receive instant visual and auditory feedback, fostering a dynamic learning process. This hands-on approach within the VR environment enables them to internalize the knowledge effectively, bridging the gap between theory and practical application. By the end of Level 1, participants will have honed their ability to recognize and differentiate between various rigging components accurately. Equipped with this essential knowledge, they will be well-prepared to progress to Level 2, where they will practically assemble these components into basic rigging configurations, all while harnessing the power and potential of VR technology.

Fig.4 Rigging System Components

3.3. Level 2 - Basic Assembly and Secure Rigging

With a solid understanding of rigging components acquired in Level 1, trainees progress to Level 2, where they embark on the practical application of their knowledge in a virtual setting. In this stage, participants will immerse themselves in the VR environment to virtually practice creating various basic rigging assemblies, honing their skills in a risk-free and controlled space. Within the VR environment, trainees will have access to an array of virtual rigging components, including slings, shackles, hooks, and spreader bars, similar to what they encountered in Level 1 as can be seen in Figure 4.

They will have the freedom to select and manipulate these components to create different rigging configurations, such as single-leg slings, double-leg slings, and bridle slings. Real-Time Feedback: As trainees assemble the virtual rigging configurations, the VR system will provide real-time feedback on their actions. Visual indicators and audio cues will ensure that they correctly balance loads and securely fasten each component, enhancing their understanding of proper rigging techniques. This immediate feedback mechanism reinforces safe practices and encourages trainees to adjust until they achieve accurate rigging setups.

One of the feedback mechanisms used to enhance the learning process, is through highlighting the proper location of each component within the overall assembly as can be seen in Figure 5. This to ensure that the trainee would not require the aid of external factors and their learning journey would be self sufficient using the rigging training model only.

Fig. 5: Different Basic Rigging Assemblies

To enhance engagement and challenge trainees further, the VR program will introduce interactive challenges. These scenarios could include lifting differently shaped loads, coordinating multiple rigging components simultaneously. By navigating through these challenges, participants develop a deeper understanding of rigging complexities and learn to adapt their skills to diverse situations. Throughout Level 2, the VR training program follows a progressive approach, starting with simpler rigging configurations and gradually advancing to more complex setups. This gradual increase in difficulty ensures that trainees build their skills step-by-step, instilling confidence and proficiency in rigging operations.

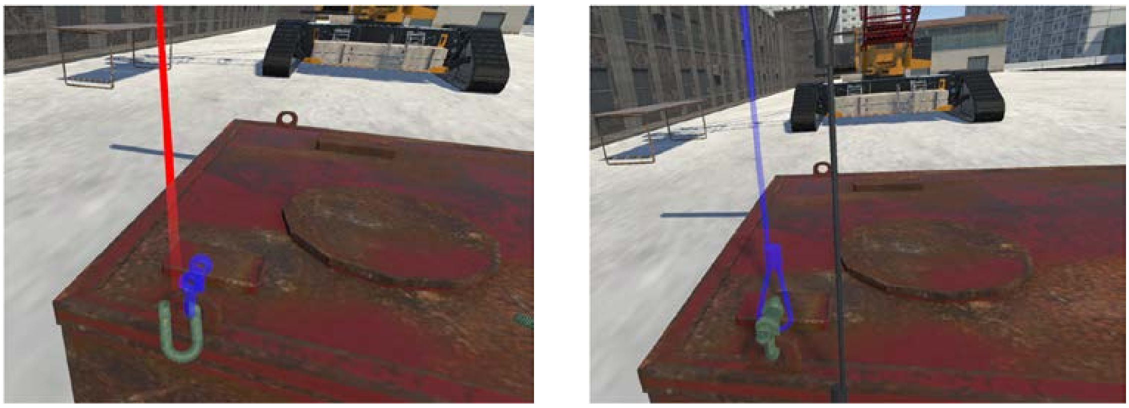

Fig.6: Training Feedback Mechanism

3.4. Level 3 - Advanced Assembly and Simulation

Level 3 represents the pinnacle of the VR Crane Rigging Training Program, where trainees are exposed to advanced rigging assembly exercises and sophisticated simulations. In this stage, participants take their skills to new heights as they tackle complex rigging scenarios, further solidifying their expertise and decision-making abilities.

In level 3, trainees are tasked with creating complete rigging modules from scratch within the virtual realm, similar to those shown in Figure 6. These modules involve intricate configurations and incorporate multiple components, without any guidance, applying what they learned in the previous levels. The VR environment provides an extensive library of rigging equipment, allowing trainees to experiment with various combinations to achieve the best setups.in some scenarios, the participants are not provided with the optimal component and are expected to produce rigging assemblies with the available components, preparing them for unpredictable scenarios in the field.

An integral part of level 3 enables trainees to evaluate the structural integrity and safety of their virtual rigging setups. After assembling and selecting a rigging configuration, a lifting simulation is used to assess the system's stability and provide immediate feedback on potential weaknesses or hazards. This invaluable feature allows trainees to identify and rectify errors.

Fig. 7: Different Advanced Rigging Assemblies

Through out the training process, the VR system records their performance metrics, allowing for detailed analysis and evaluation of their skills and decision-making capabilities. This data-driven approach enables trainers to identify areas of improvement and tailor further training to meet individual needs.

3.4. Level 3 - Advanced Assembly and Simulation

After developing the training procedure, a set of tests were done by the authors and other research team members at the University of Alberta to assess the effectiveness of the training and optimize the movement and interaction systems used throughout the training. Furthermore, the trainees were asked to choose which locomotion system was to be used when moving, and the teleportation movement system was deemed more user-friendly than continuous movement. Other concerns were tackled, and the overall quality was enhanced. In terms of interaction, some users had some difficulties getting used to the interaction system, but this issue was mitigated with more system usage.

Finally, the participants expressed that realistic graphics and environment improved their understanding and feeling of the tasks. However, they would eventually get fatigued when exposed to longer durations of using the model.

4. CONCLUSION

In conclusion, in this work, a framework for training inexperienced riggers using fully immersive VR was developed; the developed framework is expected to enhance the overall safety in crane-related operations as well as mitigate the number of incidents on construction sites that are caused by inadequate training, inappropriate rigging assemblies and human error. The expected improvements result from customizable and realistic training procedures that follow the health and safety regulations and the relevant training standards currently being used to train riggers and crane operators.

The framework performance was tested on a limited number of students and researchers with experience in crane-related operations. However, further plans to have a more extensive and detailed assessment of the performance of the training module are planned in the works to follow.

Furthermore, Future works include using other objective methods to further assess the developed model's validity. These objective methods would be used to provide a detailed comparison of the behavior of workers under training using VR and traditional methods—moreover, the measurement of vital signs to understand the impact of stress on their performance. This research can also be expanded on by creating a digital twin of the construction site and the rigging assemblies and then assessing the validity of the rigging assembly in real-time, allowing the workers to validate the lift in the virtual environment and modifying the actual assembly to minimize the possibility of an incident.

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APPLICATION OF DIMINISHED REALITY FOR CONSTRUCTION SITE SAFETY MANAGEMENT

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ABSTRACT: *Safety management in construction sites has always been one of the most sensitive aspects of the AECO industry and a problematic that recalls the complexity of such a multifactor domain. The high number of work accidents that occur on construction sites is also caused by the fact that not all the information to work safely is always available. For instance, visibility during some maneuvers is a key aspect of safety in operations, and this is often impeded due to the layout of the construction site and working methods, especially in the use of some equipment. The latest approaches in order to overcome complex situations is represented by the Digital Twin paradigm. This approach has among its main criticisms:1) the way of connecting physical reality and its digital replica and 2) the system for exploiting the combination of real-time data and digital applied intelligence for supporting operations on site. This paper proposes a framework for the development of digital twin of the construction site. An application of augmented reality that exploits the concept of diminished reality and workers location detection will improve visibility during critical operations.*

KEYWORDS: *Diminished reality; Augmented Reality; Health and Safety; Building Information Modelling; Digital Twin; Construction Site Management.*

1. INTRODUCTION

Safety in construction has always been a major issue that impacts the industry in terms of efficiency and cost. Construction is in fact one of the most hazardous industries due to its dynamic, temporary, and decentralized nature (Li et al., 2015). Among all economic activities, with the exception of oil, coal, and mineral extraction, the highest shares of serious incidents are recorded precisely in the construction divisions, which record rates above 35 percent. In the five-year period 2014 - 2018, compared to cases that occurred in other sectors, events in construction showed a higher prevalence of risk factors related to the predisposition of work environments (19% vs 12%) and procedures implemented by the injured (40% vs 47%) (Inail, 2022). These statistics focus our attention on two aspects: 1. The worksite is a place that by its conformation and nature carries a high percentage of risk; 2. The proper execution of procedures is a critical aspect that should be worked on to reduce its percentage of risk that is the highest among all (Li et al., 2015).

The traditional approach to safety also referred to as Safety-I (Martins et al., 2022) involves working to reduce the number of adverse events as much as possible. This most often involves using methods to counter or prevent the occurrence of misbehavior (e.g., audible warning systems on machinery) or to limit the effects should they eventually occur (e.g., individual and collective prevention devices). This approach involves having to envision all possible adverse scenarios so as to provide methods to counteract possible adverse outcomes. This is a continuous chase that however struggles to take into account a fundamental aspect that characterizes construction sites: their high complexity (Fang and Wu, 2013). Difficulty in standardization of procedures, complicated production processes, temporary organizational structure, relationships between stakeholders, and variable workplaces are some of the factors that contribute to the deep diversification between construction sites and other industrial production sites (Li et al., 2015). All these factors provide the backdrop for another crucial aspect that is encompassed in the concept of complexity and that is the need to manage the unexpected, which in terms of safety can be translated as dealing with new, variable and real-time risks and hazards.

In this context, the use of new technologies to collect and analyze real-time data from the construction site can be a disruptive innovation (Teizer et al., 2022). A push in this direction is also provided in the Italian context by Law 36/2023, which in Annex I.9, article 12 letter m states: *"In the formulation of information requirements by contracting stations, specific uses, operational methodologies, organizational processes and technological solutions may be defined as objects of evaluation for the purpose of rewarding, with reference to the execution phase of works, to digitally increase health and safety conditions at construction sites."* However, there are still unresolved issues in this regard that prevent widespread and pervasive use of these methods in the real environment. On the one hand, real-time on-site data collection itself encapsulates within it several problems: the sensorization of construction sites (workers, vehicles, materials), methods for collecting images that can be

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Alessandra Corneli, Berardo Naticchia, Massimo Vaccarini, Alessandro Carbonari, Francesco Spegni, *Application of Diminished Reality for Construction Site Safety Management,* pp. 195-205, DOI 10.36253/979-12-215-0289-3.19

exploited to apply artificial intelligence, the possible need to have to provide power in the open environment to IoT devices, and the lack of a unified framework where to channel and integrate the collected data. On the other hand, information derived from analyses, short-term simulations or application of artificial intelligence should increase the knowledge of the stakeholders involved and thus in the interest of safety management they should be made immediately available on site in order for being used by operators, safety managers and site managers. This aspect represents a great complexity because making content usable on site requires finding quick and effective methods of communication both in terms of sending the data and visualizing it at the construction site. Augmented reality is a technology that has great potential in terms of visualization. Indeed, the use of holograms superimposed on the real-world view makes it possible to add an information layer that can show aspects not visible to the human eye or enrich knowledge with information from analysis of previously submitted data. In some cases, however, what is needed is not so much to add a layer of knowledge as to remove something that impedes the view. There is for this purpose a specific class of augmented reality that is called diminished reality (Cheng at al., 2022).

The purpose of this research is to apply the concept of diminished reality to construction sites in order to support operations with regard to risks related to operator safety. The proposed framework and the first experiments developed involved moving loads with a crane work scenario, including work at height, where the operator of the vehicle has a not fully unobstructed view. The application of see-through diminished reality allows the crane operator to visualize any worker placed in the vicinity of the load through the use of a depth camera and artificial intelligence. Innovations of the proposed system include: 1. Visualization by the operator not only of the relative position between workers and load but also of the orientation of the workers' bodies. This information makes it possible to understand whether the worker is aware that he or she is near a moving load or whether there is a risk of catching the worker by surprise (in case it is shown that the subject is with his or her back to the load). 2. An automatic procedure that transforms the visualization from solid to wireframe of objects that are opposed between the machine operator and human figures detected by the depth camera. In this way through a two-way line of communication and interaction between the actual construction site and a digital representation of it, a Digital Twin (DT) type approach will be achieved in which data obtained are processed and sent back, after the necessary analysis, directly to the site real time use. The system proposed in this article makes more sense at large, complex construction sites where the expected safety costs are higher and therefore allow for the implementation of new technologies.

2. LITERATURE REVIEW

The use of innovative technologies such as virtual (VR), augmented (AR) and mixed reality (MR) in the construction industry has found different levels of application due to the differences between them. Applications using augmented and mixed reality have long since found their use in construction sites. Chalhoub et al., 2018 proposed a method for electrical system component's location visualization on site using mixed reality and head-mounted displays. A similar way of exploiting MR is proposed in recent times also by Dallasega et al. (2023) for MEP components installations in general. A number of applications of AR and MR in construction sites still refers to way for showing design information or building components specifications in a more straightforward and easy understanding way (Carbonari et al., 2022; Yoon et al, 2022; Sabzevar et al, 2023; Pendersen et al, 2020; Um et al., 2023).

As far as worksite safety is concerned, however, most applications focus on the possibilities of leveraging these technologies for operator training. Boschè et al. (2015) proposed a novel MR system uniquely targeted for the training of construction trade workers. One of the aims of this paper was to enable trainees to experience construction site conditions, particularly being at height, in different settings. Anyway, the majority of these applications makes use of VR or Augmented virtuality (Wolf et al, 2022) which means that the operator is transported completely into the virtual world to carry out serious game-like experiences but without testing in the real world or with operations carried out live. Jelonek et al. (2022) developed a VR application for training operators in the use of cutting equipment on site introducing in the serious game procedures to follow in order to be sure that all the involved personnel is following all safety prescriptions. Wolf et al. (2022) developed a serious game for inspector job simulation in a complete virtual environment. Speiser and Teizer (2023) tried to move forward introducing the concept of digital twin for construction safety training in order to link various data sources to generate a Virtual Training Environment (VTE) automatically. However, few applications are yet attempting to bring these technologies on site to provide real-time assistance. Nguyen et al. (2022) started to work on skeleton recognition for action recognition on site but they have not developed an AR visualization on site yet. Eiris Pereira et al. (2019) combined training and augmented reality but directly on site for reporting situations with danger of falling from height.

One aspect that is still underemphasized in the construction world is that sometimes it can be very useful that information is taken away rather than added, and in this sense the application that should be considered is that of Diminished Reality (DR) (Mann et al., 2002). While AR and MR superimpose virtual objects on the real world to enhance reality by placing new objects among real objects or extending real objects with virtual objects (Mori et al.,2017), DR deliberately removes parts of a real-world scene or replaces them with computer generated information (Mann & Fung, 2001) and it can be considered a subtype of AR. Based on computer vision techniques, unwanted image elements are detected and replaced by other image elements, creating an overall plausible and consistent impression for the viewer. The idea in diminished reality is to virtually remove something from the view. There can be identified different techniques for diminished reality implementation. In one kind of approach the object to be removed needs to be detected and the corresponding image area needs to be filled in with a texture that seems to belong to the background. In image processing terms, this kind of filling-in operation is called image inpainting (Siltanen, 2017). Another approach discusses a way of representing occluding objects as semi-transparent. This visualization technique is called AR X-ray vision, see-through vision, or ghosted views. Semi-transparent representation is useful for seeing through car interiors and walls (Mori et al., 2017). In automotive settings, a number of see-through displays have been incorporated. In Samsung's Safety Truck, for example, live video images were displayed on the back of the truck, effectively granting trailing drivers the ability to 'see through' the truck.

The very first approaches to DR aimed to lower the saturation of some areas to force an observer to face other regions and virtual objects overwrote undesirable real objects to hide the real information (Mann, 1994). After that this technique was used for different purposes: to remove a person from Google Street View pictures to protect his or her privacy, to remove a person in a video, to remove a vehicle in front of the driver, to remove a baseball catcher to visualize the view of the pitcher from a view behind the catcher, and to generate a panoramic stroboscopic image (Mori et al, 2017). In the case of see through applications one of the methods to provide the current state of the hidden area in the main view is the same as that used by Zokai et al. (2003) that used two additional cameras as hidden background observers to erase from the main view pipes in a factory. Mori et al. (2017) constructed light fields with a real time multi-camera system and removed a viewer's hand from the perspective to visualize the viewer's workspace occluded by his or her own hand. Queguiner et al. (2018) presented a diminished reality application running live on consumer mobile devices. In their pre-observation-based approach, the clean 3D scene, free of undesired objects, is scanned beforehand and reconstructed as a high-resolution textured 3D model. Many see-through DR literature tends to investigate more computationally efficient approaches focusing on compensating real–virtual boundary in screen space. Thereafter, semi-transparent or wireframe representation is performed to improve user depth perception. These representation methods will be useful for avoiding the danger of a collision with the diminished objects. In this regard, Peereboom et al., 2023 presented a system that exploits DR for avoiding collisions between pedestrians and cars caused by poor visibility, such as occlusion by a parked vehicle. In one of the solutions, they proposed the occluding vehicle has been made semi-transparent. Still recently, Cheng et al. (2022) proposed a study on users' perception of diminished reality and its possible applications.

However, the concept of DR is still little exploited in construction although Klinker, Stricker and Reiners (2001) develop the first examples of diminished reality in the field of construction with two very significant examples: in the first one TV antennas located on a hill are removed from the view within which the work that will replace them is later placed so that it can be visualized in its chosen location. In the second case given as an example, the installations below a wall are shown in the form of holograms.

This research aims at exploiting the concept of diminished reality for construction sites operations efficiency and safety. The innovation of the system proposed lays in the combination of skeleton recognition, which provide operators position and field of view, and the automatic procedure that detect obstacles and made them visualized as a wire frame model. The integration of different technologies for onsite application is also another key aspect.

3. DR FOR CONSTRUCTION SITE SAFETY MANAGEMENT SUPPORT

The system proposed in this research is a diminished reality application for supporting safety management at construction sites. The development focused on a specific case and that is load handling by crane. In the case of cranes maneuvered from the ground, but not only, there are situations in which visibility can be reduced: work at height in which the support is not clearly visible, maneuvers on the construction site in which the placement of material takes place beyond already built constructions. For this reason, a viewer that supports the operations coordinator in visualizing possible hazardous situations can assume great value (Fig. 1). To this end, we focused in this work on visualizing workers in locations hidden from view.

It was decided to proceed with localization and visualization through depth camera with a twofold advantage: on the one hand, this instrument returns the skeleton that allows us to understand how the worker is placed and oriented; on the other hand, the fact that only the skeleton is communicated removes a number of privacy issues. In this system then it was planned to also instrument moving loads, with sensors (UWB inside and RTK outside) in order to be able to communicate this data to the operations coordinator as well. Finally, the developed application involves the transformation of the obstacle object visualization from solid to wireframe. Such a system finds its application not only in the highlighted case but also in many other site operations such as demolitions where knowing what lies beyond certain elements could be crucial.

Fig. 1: Diminished reality for construction site.

4. METHODOLOGY

The methodology followed in this research for improving the safety of workers in construction sites through the exploitation of DR is shortly described in Figure 2.

The first step is setting up a localization framework covering the entire construction site. Such framework should be a *real-time system* capable of attaching spatial coordinates to any entity, object or person, moving around in the construction site. The specific technology employed for this step can vary depending on several aspects, e.g. whether the construction site is outdoor or indoor, or whether we are considering an existing facility to be recommissioned or instead a new building or infrastructure to be built. For complex scenarios, multiple technologies may coexist at the same time to localize objects and people in different areas of the overall construction site. In such a case a problem arises of allowing a seamless integration of different localization systems to provide a homogenous notion of localization on the construction site. The core idea behind the localization framework is to support the detection of safety hazards so as to prevent incidents.

A second step of the methodology is the setup of a heterogeneous network of sensors continuously monitoring the activities in the construction site. The sensor network may employ very different devices both for their technological characteristics and for the kind of data collected (e.g. temperature sensors, cameras, NFC tags, etc.). The basic requirement for each sensor in our methodology is that it must be able to attach a precise timestamp and a precise set of coordinates relative to the localization framework set up. This would witness when and where the information was sensed in the construction site.

A third step is the setup of a DT Platform integrating several sources of information operating on and off the construction site. For instance, interpolating information coming from the construction design together with data collected by the network of sensors the platform can provide the most updated "picture" of the building or infrastructure being realized. The DT Platform is also responsible for managing and harmonizing the several data models used to express the information coming from the different (internal and external) sources, e.g. by using linked data or ontology-based semantic data integration procedures.

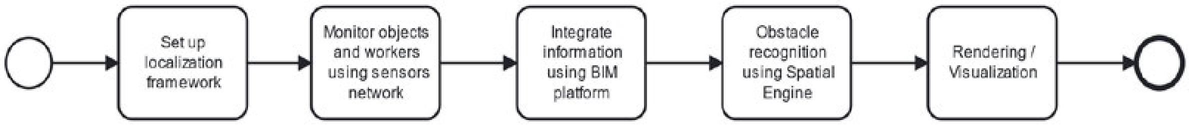

Fig. 2: Methodology for applying Diminished Reality to construction site safety.

Next, a Spatial Engine should be implemented that processes all the spatial information from the BIM models, the persons equipped with DR viewers, the sensors deployed through the site, the vehicles and all the various agents acting within the site. Given the position of a person using a DR viewer, its main role is to determine which agents and BIM objects are of interest for him/her and to provide the corresponding data streaming. Moreover, by exploiting the information stored in the CDE, the Spatial Engine is the place where possible spatial interferences can be detected, forecasted, and notified at run time to the involved agents in order to prevent injuries.

Finally, a DR visualization tool is in charge of rendering holograms mixed with the real objects of the construction site in order to allow the observer to view also those hidden objects that can be involved by the ongoing operations. The obstruction is determined in real-time based on the observer's point of view and the position of the moving objects given by the sensory data: when a BIM object is hit by the ray joining the observer with a moving object, this BIM object is classified as obstructing and it is rendered as wireframes thus making visible the virtual objects behind it that reproduce their invisible real twins.

In the following sections this methodology is applied starting with the indoor localization framework. The sensor network has been set up with a depth camera and two location tags. The former is a special computer camera with two "eyes". By merging the visual information coming from them, it can compute the distance (or depth) of objects and bodies w.r.t. its point of view, when they appear in the picture. The chosen depth camera also provided advanced artificial vision software capable of recognizing the position of core joints in the skeletons. This information can be exploited to know the real-time position and orientation of an individual or of a crew of workers. As a consequence, it is possible to relate this information the one coming from the tag attached to the load lifted by the crane in order to know the exact relative position and the risk of the workers to be hit. A mixed-reality head-mounted display (HMD) is used as visualization tool where the BIM model of the construction site and signals coming from the sensor network (e.g. the position of the workers in the construction site coming from the depth camera, as well as the position of the depth camera itself, and of the crane load) are downloaded from the DT platform together with the spatial simulation results. Also the head-mounted display DR application can download from the DT platform information about the 3D objects that hinders the view of workers and the load when the crane is operating thank to ray-tracing data transmission. The ray-tracing technique uses basic geometry in order to select all the 3D objects (e.g. walls, doors, columns, etc.) that lay in between the user viewpoint and the objects returned as obstructions (i.e. the workers and the crane load) and then the platform sent them back made transparent in a wire frame visualization.

5. SYSTEM ARCHITECTURE

The architecture of the system proposed in this paper is the one depicted in Figure 3. In accordance with what was previously described in the methodology paragraph in this section the specific devices and components of the system will be made explicit. For what concerns the localization of the operators, we chose to use a depth camera and specifically a ZED 2i. This device made possible two things: 1. recognize the skeleton of the workers; 2. place the skeleton in the virtual space once the position of the camera in the real space is known. The ZED 2i camera provides the streaming of the joints of the skeleton, which were set equal to 18 points.

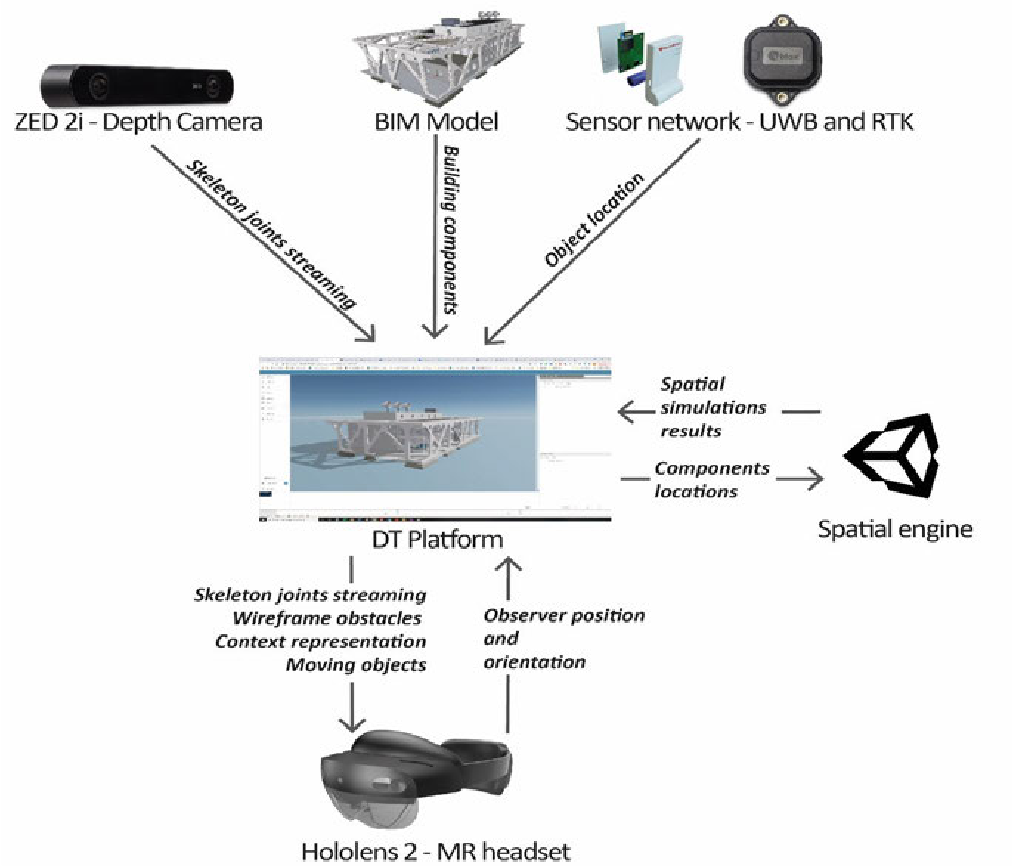

Fig. 3: System architecture and data flow.

For space modelling it can be used a BIM model provided in ifc format. This type of space modelling contributes in modelling the different building components enabling at a later stage to go and select one by one the objects that represent obstacles to workers visualization. In the development here proposed, Autodesk Revit was used for BIM modelling. Moreover, in the case of the construction site where the presence of the elements is dependent on the progress of the work, the combination of ifc files with a timeline also makes it possible to analyse what would be visible and what would not be visible at a precise moment in the construction.

Finally, since not only the workers need to be located but there are other components of the worksite whose location is important to know, a number of sensor networks can be implemented. These vary as needed. In the case taken as an example in this article, two types of sensors were referred to: GPS RTK tags and UWB tags. Although the GPS RTK localization system could not be integrated into the indoor tests reported in section 6, its suitability for outdoor applications is shown by its quite high accuracy reported by technical sheets [Datasheet], which was confirmed by very preliminary trials performed by the authors. But this is going to be used in future research developments. For the purpose of the indoor tests subject of this paper, contextual infrastructure was monitored by means of UWB anchors. In any case, it is worth remarking that both types of sensors can be used to communicate position data.

Moving on to the other components of the system, a platform, resulting from the development of the research project "A Distributed Digital Collaboration Framework for Small and Medium-Sized Engineering and Construction Enterprises" (PRIN 2017), is used. This platform uploads BIM models in ifc format, allowing browsing and querying. The platform then allows the integration of data from a variety of heterogeneous sources (in this case skeleton joints from ZED 2i and location data from sensors) allowing them to be located in space or linked to components (e.g., modeled building objects). In this way it is configured as a real DT platform.

As for the spatial engine, this receives the necessary information and thus the positions of workers and moving objects (provided by UWB or GPS-RTK). The purpose of the spatial engine is to perform real-time processing about spatial interference and then transmit it to the platform, which will also relate it to the components of buildings in space so as to identify objects of obstruction to operator's view.

Finally, the last component of the system is an MR head-mounted display whose use has two purposes. The first is to enable the display of holograms for a diminished reality visualization. The second is to provide the position and orientation of the observer. The Microsoft Hololens used as the MR provider receives the information directly from the platform and thus the visualization of the skeleton joints, the model of the surrounding environment, the positions of moving objects, and objects identified as obstacles and whose representation is then modified by the procedure to change from solid to wireframe. In order to achieve a consistent visualization, the Hololens transmits to the platform the position of the operator with respect to the modelled space and information about the orientation of the head. In this way it is possible to precisely calibrate the sample scenario.

6. DIMINISHED REALITY APPLICATION

The experiment was conducted using a Python application sensing the skeleton information coming from the depth camera ZED 2i through the Python SDK. In this application, the camera acquired two video streams at 30 fps, and once every 3 frames the skeletons information where encoded as JSON objects and published using the MQTT protocol. For debug purposes, the position of workers' skeleton joints where highlighted in a live video stream (Fig. 6 b). This resulted in 10 MQTT messages sent per second. The DT Platform subscribed the topic on the MQTT broker, thus receiving the skeleton signal from the Python application. The DT platform was in charge of sending the skeleton signal as well as the BIM design and the location of the camera, the Head Mounted Display, and the object moved by the crane, to the Spatial Engine. The latter was responsible for detecting in real-time the list of obstacles in the BIM design and passed it to the Head Mounted Display, together with the position of the workers and the crane load w.r.t. the Head Mounted Display.

The logic behind the Spatial Engine detects obstacles using ray-casting, a technique implemented by the Spatial Engine which returns a list of objects hit by a hypothetical ray departing from a source position towards a given direction, and having a length bounded by a given maximum value. To reach our aim, we need to use the user's viewpoint as source position of the ray-to-be-casted, next we need to cast a ray on each direction corresponding to each joint of the workers skeletons detected by the depth camera and each object moved by the crane; finally, we must set as maximum length of the casted rays the actual distance between the user and the joints or moved objects.

7. DEVELOPMENT AND CASE STUDY

Feasibility tests of the developed application were carried out in the DC3 laboratory of the DICEA department of the Polytechnic University of Marche. In this case since a crane was not available, the overhead crane carriage inside the laboratory was used to simulate the suspended load in motion. The hook of the bridge crane was instrumented with a UWB position sensor which sends data to the platform (Figure 4). The laboratory is equipped with UWB anchors placed at the corners of the room for precise position sensing.

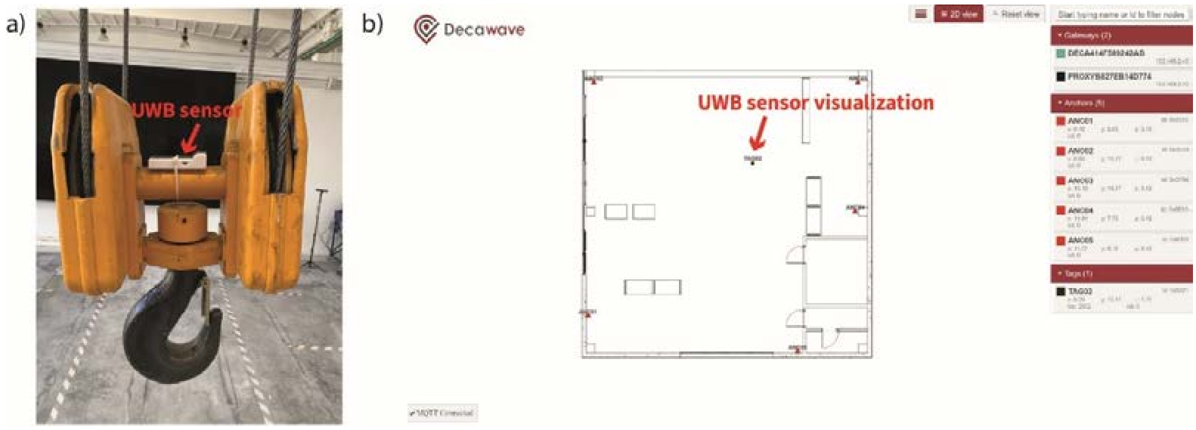

Fig. 4: a) Bridge crane hook instrumented with UWB sensor; b) UWB sensor visualization in the space inside the platform.

Next, the ZED 2i camera was placed as seen in Figures 5 and 6 a). The information that the chamber returns through the recognition of the skeleton joints is as in Figure 6 b). The orientation of the worker is also detected as the blue joints detect the left side of the body while the red joints detect the right side. In this way it is possible to understand which direction the worker is looking at and thus whether in the presence of a moving load he is presumably aware of the presence of the load or whether his being from behind identifies a situation of greater danger as he may not have noticed that something is moving in his vicinity.

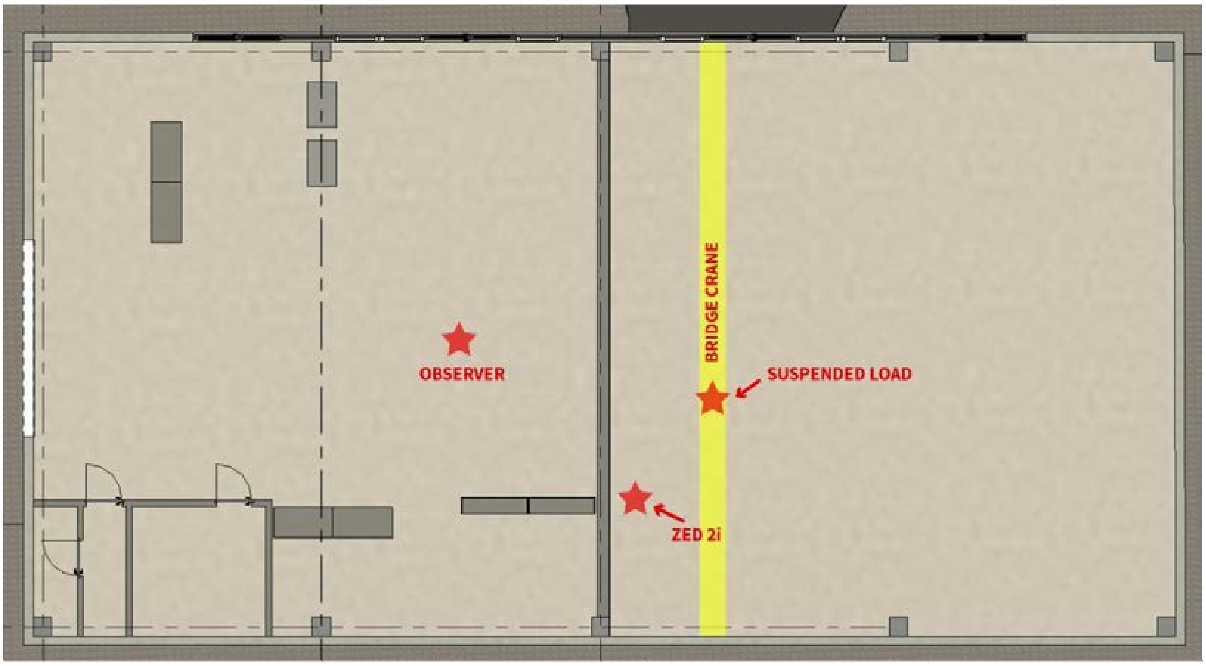

Fig. 5: Components position inside the laboratory.

The test performed reproduced the same conditions shown in Figure 1. The laboratory is placed in a shed divided in half by a wall 3.5 m high, about half of the total height of the structure. Figure 5 shows the location of all components for the experiment in the laboratory. In order to verify the actual operation of the application for the developed diminished reality, the operator wearing the HoloLens stood on the left side in the floor layout of the shed. Looking toward the partition wall (Fig. 7 a)) the HoloLens showed the wall in wireframe visualization and the skeleton points of the operator who was moving around the load on the other side of the room. In this first processing the positioning of the load was not implemented in the hologram visualization although it was present as data in the platform. Again, it is possible to observe the differentiation of blue and red colours for the left and right side of the body respectively which allows the worker observing the scene to understand the orientation of the worker.

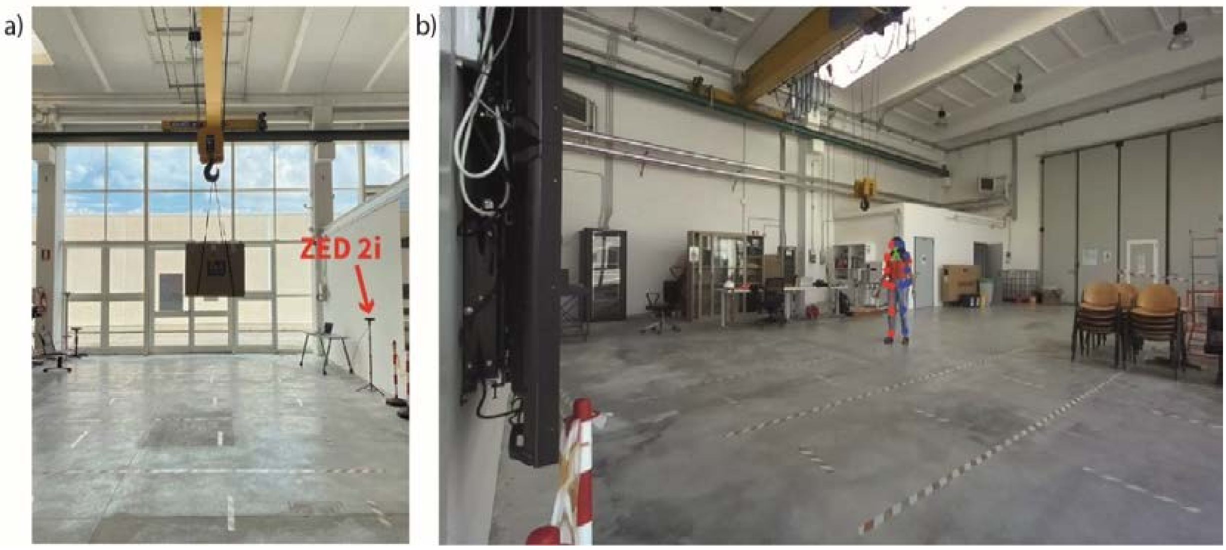

Fig. 6: a) Load position and ZED 2i location; b) Depth camera vision and skeleton joints recognition.

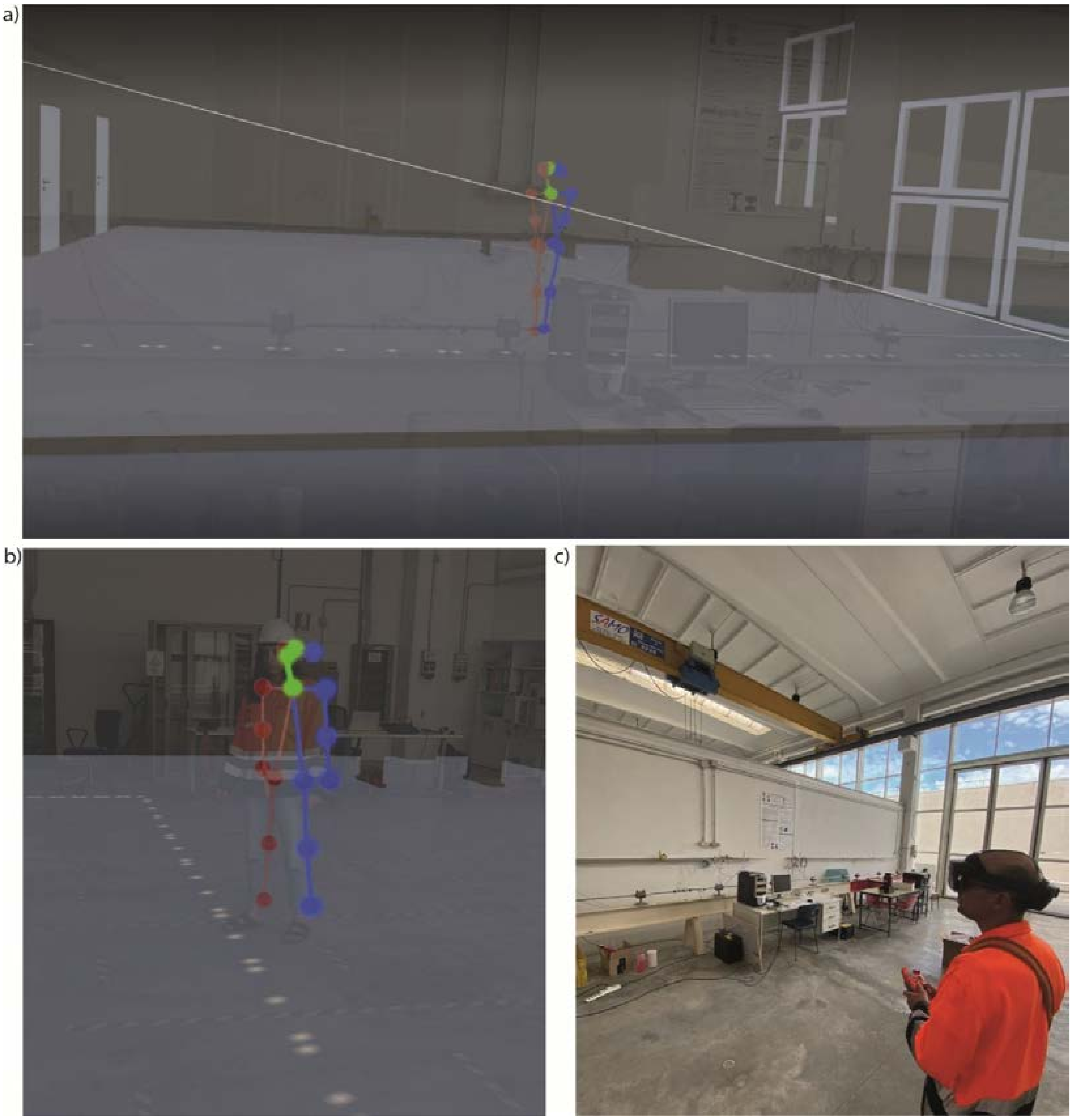

Fig. 7: a) Vision from inside the HoloLens (other side of the wall) ; b) Vision from inside the HoloLens (same side of the worker framed); c) operator with the HoloLens and the bridge-crane remote control (other side of the wall).

8. CONCLUSION

This paper presents an application of diminished reality for safety management support during operations at a construction site. The proposed system involves the use of depth camera and sensors for locating components of interest and implements the development of a DT platform for real-time management. The system thus developed allows for optimization in the number of sensors that can be placed in strategic areas (depth camera) and alternately on moving loads or equipment to be monitored at the stages when they are expected to be utilized. Initial experiments of the application of this development were carried out in the laboratory by reproducing conditions similar to those at a real construction site. The next steps will concern the implementation of the visualization inside the HoloLens of the position of the moving load and tests in outdoor construction sites thus having the possibility to test also the visual rendering of holograms in the open air that could be an obstacle to the optimal visualization for operators.

9. ACKNOWLEDGMENTS

This work is supported by the Italian Ministry of Education, University and Research, PRIN 2017 Project: "A Distributed Digital Collaboration Framework for Small and Medium-Sized Engineering and Construction Enterprises".

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DRIVING SIMULATOR FOR ROAD SAFETY DESIGN: A COMPARISON BETWEEN VIRTUAL REALITY TESTS AND IN-FIELD TESTS

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ABSTRACT: V*irtual reality simulations conducted by driving simulators represent a methodology to assess both the quality of road design and road safety in a safe, controlled, and replicable environment.*

Nowadays, there are numerous studies that use driving simulators to analyze the driver's response when specific road safety treatments are planned before these are implemented. This approach allows the road designer/scientist to estimate the potential safety effectiveness of the countermeasure/design configuration considered.

However, although virtual reality simulations are potentially extremely useful in the evaluation of road configuration design and treatments effectiveness, they also have cons. The two most important are the limitations in the reproducibility of the realworld environment and the difference in drivers' behavior due to the awareness that they are conducting a test.

In this context, our research compared the data collected during virtual reality experiments with those collected in the field with an instrumented vehicle, after a few years from the implementation of the specific safety measure on a real road. Statistical analyses were conducted to compare the results of the two experiments to demonstrate the reliability of the virtual simulations and to identify the limitations.

KEYWORDS: *driving simulator, road safety, virtual reality, road safety treatments, road safety measures effectiveness, in-field test*

1. INTRODUCTION

Making safe roads and decreasing the number of accidents, deaths and injuries on the roads is one of the greatest challenges of this century.

Nowadays technology allows scientists, engineers, and technicians to approach road safety including also human behavior. Virtual reality represents one of the instruments that allow road engineers to understand and evaluate in a safe and controlled environment how both road configuration and other contingent factors, affect human behavior.

When an unsafe road section is identified as a "black spot", e.g., through an analytical accident analysis, the Road Administration (RA) works "to change" the road configuration, improving aspects related to road traffic safety. The solution selected is then implemented on the road and only a few years after the intervention, it can be observed whether the proposed countermeasure has been effective (or not). This type of reactive approach requires investing high budgets to correct the road deficiencies and waiting years to see if the solution proposed was useful in the accident mitigation phenomenon (not always proving its effectiveness).

The use of virtual reality approach, instead, allows to investigate the described phenomenon in a proactive manner (before the accident occurrence), using a controlled, safe and ethical test environment (Calhoun and Pearlson, 2012). Virtual reality also allows to perform a safe, controlled, reproduceable and standardized experiment (de Winter et al, 2012). In fact, the researchers define the "road environment" within a scenario able to describe the main phenomena to be studied, for example, different road geometry (Bassani et al., 2019b; Bobermin at al., 2021; Montella et al., 2018), different intersection layout (Danaf et al., 2018; Kekez et al., 2022) or different cross section organization (Bella, 2013; Ben-Bassat and Shinar, 2011; Mecheri et al., 2017; Domenichini et al., 2018); or introducing events describing specific road users' interactions or limited sight distance (e.g., driver-pedestrian with occlusion, etc.) (Bassani et al., 2019a; Domenichini et al., 2018)

Unfortunately, the use of driving simulators also has cons to be considered. Limited physical, perceptual, and behavioral fidelity of the instrument (driver simulator) affect both the experimentation reliability and the driver's interest in the test, especially if the vehicle cannot reproduce the vehicle performances in an accurate way (de Winter et al, 2012; Boda et al., 2018; Pawar et al, 2022). The possibility to transfer the study results to "an actual road safety countermeasure construction" needs the results to be evaluated in terms both of fidelity and validity. The first validation processes were defined since the last century (Blaauw, 1982; Klee et al., 1999). The term

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)

"fidelity" has been used to describe the ability of the driving simulator to reproduce the sensory stimuli present in a real driving environment. This ability was strongly dependent on the quality of the equipment (e.g., motion system, projector, screen and display, simulacrum and sound) (Kaptein et al., 1996). Wynne et al. (2019) conducted an extensive literature review concerning driver simulator validation studies. According to the definition given in Blaauw, the word "validity" describes the ability of the study to accurately represent the drivers' behavior in a real world. The study considered two types of validity: absolute validity and relative validity (Blaauw, 1982).

The most used parameter to check the quality of the driving simulator results was drivers' speed (Cao et al., 2015; Bella 2008; Bham et al., 2014; Yan et al., 2008; Branzi et al., 2017). Often the speed was coupled with other parameters describing the drivers' performance such as acceleration/deceleration or lateral position (Blana and Golias, 2002; Chen et al., 2021; Kazemzadehazad et al., 2021) and drivers' reaction time (McGehee et al., 2000; Engen, 2008).

The literature shows that in the analysis of road safety the use of the driving simulator represents a great opportunity for road engineers and scientists to assess preliminary the impact of a specific engineering treatment. The virtual reality evaluation allows also to define the best safety solution with reference to the specific road safety objective and without any implementation cost. The objective of this research is to complete the research conducted in 2017 (Branzi et al., 2017) also investigating the ability of the LaSIS driving simulator to reproduce the drivers' behavior when different safety countermeasures were present along the road. This validation study compared the speed profiles of the driving simulations and the real world drivers, evaluating where the results are similar and which effects could instead cause differences in drivers' behavior and in virtual reality results exploitation.

2. METHODOLOGY

2.1 Research history and overview

Via Pistoiese was studied by our research group in recent years, especially concerning pedestrian safety. Statistics on accidents in Florence always placed this street in the first places in terms of danger, especially for vulnerable road users (VRUs) (Domenichini et al., 2014).

The safety problems of the street were different, and they included the high speed, the high level of interaction between traffic and VRUs due to the strong traffic demand, the geometrical configuration (a long straight about 4 km), and the high presence of commercial activities, residential areas, and parking stalls along the road.

To improve the road safety of the area, part of the street was interested by a reconfiguration project, where numerous traffic calming measures were defined and implemented with the aim of limiting the speeding phenomena, including:

- introduction of both raised pedestrian crossings and/or raised intersections to control the speed along the section;
- installation of a raised median curb to avoid overtaking maneuvers, but which can be performed only by the emergency vehicles;
- reduction of the lane width to the standard value for this type of street;
- introduction of high perception elements to improve the driver perception of the context.

A few years before the road modification, the entire reconfiguration project was studied in virtual reality. In Domenichini et al. (2018) and in Branzi et al., (2018) the good results obtained from the experimentation were extensively described.

In 2018 the safety solutions evaluated in virtual reality were implemented along via Pistoiese and nowadays are part of the road environment. In this context a new experimentation was conducted by the authors to monitor the effectiveness of the engineering treatments over time, and to understand if the results obtained by the LaSIS driving simulator are reliable.

This latter experiment was conducted in-field with a specific device named V-BOX HD2, which is similar to a black box capable of recording the kinematic parameters of the moving vehicle. The experiment can be considered as a validation experiment for the result obtained in the virtual reality evaluation comparing speed and acceleration/deceleration behavior. Figure 1 represents the research approach and the connection between the two different tests conducted, in virtual reality and in-field.

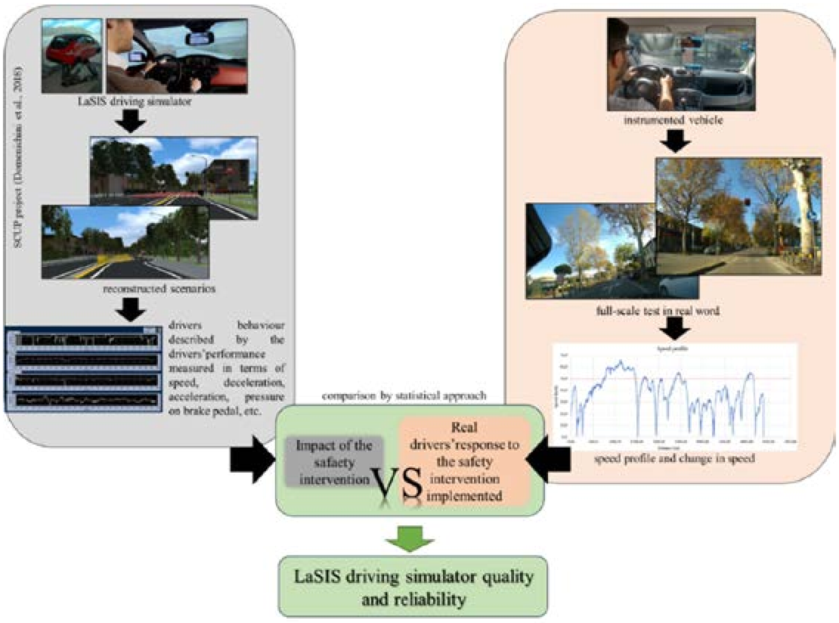

Fig. 1: Overview of the research

2.2 Detailed description of the road context

Via Pistoiese is a street located in the suburban area of Firenze, classified as an urban collector road (it serves penetration movements but also VRUs movements for commercial and residential activities). The road geometry is simple, and it is composed by one curve (R=250 m) that connects two straights which are connected to the road network with roundabout intersections. The road segment is about 4.5 km long (Figure 2).

Fig. 2: via Pistoiese (Firenze)

The cross section is about 18 m wide. On the roadside, a 2.00 m wide parking area and two sidewalks are present (1.50 m wide) on both sides. A wide cross section is dedicated for motorized traffic, and it is organized in different configurations along via Pistoiese as described below:

- different number of lanes (segments with one lane per direction and segments with one lane in one direction and two lanes in the other one);
- presence/absence of a median curb that does not allow left turn maneuvers;
- numerous and different traffic calming interventions (such as raised pedestrian crossing, raised platform in the intersection, chicanes, etc.).

In this paper, the analysis was conducted with reference to the road segment interested by the traffic calming treatments (in orange in Figure 2). In Figure 3 and in Figure 4 some comparisons between the actual street and the virtual scenario are shown.

Fig. 3: via Pistoiese: real world VS virtual reality (1/2)

Fig. 4: via Pistoiese: real world VS virtual reality (2/2)

2.3 Apparatus

Two different apparatus are used in this research, the LaSIS Driving Simulator and the V-BOX HD2.

The LaSIS Driving Simulator is a motion-based simulator, equipped with a full-scale Lancia Y simulacrum fixed on a 6 degree of freedom Stewart's platform. The platform allows roll, yaw and pitch movement of the vehicle. The vehicle interior includes all commands normally available within a car, with a steering wheel with force feedback. The three rear-view mirrors, the central one and the side mirrors, are equipped with displays that project the scenario just traveled and complete the vehicle interior. The cabin is surrounded by a cylindrical screen about 200° wide where 4 projectors reproduce the driving environment. The sounds in the environment and in the participant's car are generated by a multichannel audio system. The data acquisition frequency of the apparatus is 20 Hz. According to the classification proposed by the literature in term of the ability of the device to emulate driving in real world (i.e., vehicle controls, field of view and kinesthetic), the LaSIS driving simulator can be classified as a high-fidelity driving simulator (Goode at al., 2013; Wynne et al., 2019)..

The VBOX HD2 system used for the on-field test consists of a mobile device, like an advanced black box, able to record dynamic information concerning the vehicle movement (such as speed, GPS position, acceleration, deceleration, position in the lane, etc.). The instrument needs to be fixed inside each passenger car used in the on-field experiment. The acquisition frequency is different for GPS and video information and respectively equal to 10 Hz and 60 Hz. The VBOX application allows to read the measurements synchronized and check in a remote analysis the information related to the recorded data (e.g., available satellites, traffic conditions, etc.).

2.4 Participants and procedure

Participants were recruited on a voluntary basis among students, staff, expert drivers and common people.

In both tests, drivers had to meet the following requirements:

- possession of an Italian valid driver's license;
- normal or corrected-to-normal vision.

Two samples were recruited composed of 48 users and 36 users respectively for virtual reality and on-site test. Samples do not contain people who drove in both tests due to the different time frame in which they were conducted (2015-2016 and 2021-2022), but mostly because the selection of the same participants can affect the drivers' behavior in the second experiment due to the previous experience in virtual reality. Table 1 summarizes the participants' characteristics.

Table 1: Participant characteristics

	Virtual reality experimentation		**In-field experimentation**	
	M	F	M	F
Gender	36	12	28	8
Age	42.2 (S.D. 12.7)		40.6 (S.D. 17.12)	

NOTE: S.D. standard deviation

Their driving experience (years of driving license possession) ranged between 3 years and 46 years. Except for 5 participants, all of them declared that they travelled at least 5,000 km in a year.

Each participant was tested individually, according to the two different procedures adopted respectively for virtual and full-scale tests (Domenichini et al, 2018; Meocci et al., 2023). Table 2 summarizes the main steps of the two-procedures adopted for the experimentations.

Table 2: Procedures summary

Virtual reality test	**In-field test**
No payment for the involvements	
Participants were not informed about the research objective	
Test duration about 35-40 min in safe and controlled environment (LaSIS laboratory)	Test duration about 35-40 min in real-word but in a defined path. No restriction of the traffic conditions was defined during the test.
The drivers' performances were recorded by the LaSIS driving simulator	The drivers' performances were recorded by the V-BOX HD2 fixed each time inside the drivers' own car

2.5 Data collection and analysis

To test the validity of the results obtained by the LaSIS driving simulator the comparison was made analysing the speed profiles obtained in virtual reality experimentation and in full-scale test.

A preliminary comparative analysis of the entire average speed profile was conducted to analyze if the simulator results showed the same patterns (and macroscopic effects) as those measured in the real world (relative validity). The comparison was made only with reference to the profile sections where there were no conditions that influenced the drivers' speed (i.e., pedestrians who cross the street in the simulation or traffic congestion in the in-field experimentation). A qualitative comparison was also carried out with reference to the V85 speed.

The absolute validity of the simulation results was evaluated by means of a statistical test. The two datasets consist of the speed measurement along via Pistoiese in virtual reality and in-field. The two datasets were preliminary verified by the Shapiro-Wilk and Levene's tests respectively for normality and homoscedasticity assumptions. In the former test H_0 states that the variable is normally distributed, in the latter H_0 states that the variables we compared had equal variance. Both the tests were conducted with a significant level of 5%.

Subsequently two tests to compare the averages of two groups and determine if the differences between them are more likely to arise from random chance were conducted, the t-Student's test for independent sample when the sample was normally distributed and the U Mann-Whitney's test, a non-parametric test, for the other samples. Both tests were conducted with reference to the null hypothesis H0: the difference in mean is equal to 0. In all cases where the null hypothesis was rejected, also the effect size was determined by the d-Cohen metric. This allows to define the strength of the relationship between two variables compared.

Finally, according to Losa et al., (2013) a regression analysis was conducted to investigate how the driving simulator experimentation reproduces the real-world performances, considering each road segment.

3. RESULTS AND DISCUSSION

3.1 Relative validity: average speed profile comparison

Figure 5 shows the result of the preliminary comparison between the two speed profiles. Specifically, in the chart were depicted the speed profile recorded in virtual reality (in red), the average speed profile recorded the in-field test (in green), the absolute difference between the two speed profiles (in light blue), and the number of lanes in the considered direction (in black). Furthermore, the red dashed line indicates the position of the pedestrian crossing axes where an event was reproduced in the virtual reality simulation (pedestrian who is crossing the street). Finally, green dashed lines indicate the position of the stop lines within the intersection and green dotted lines indicate the position of the pedestrian crossing axes.

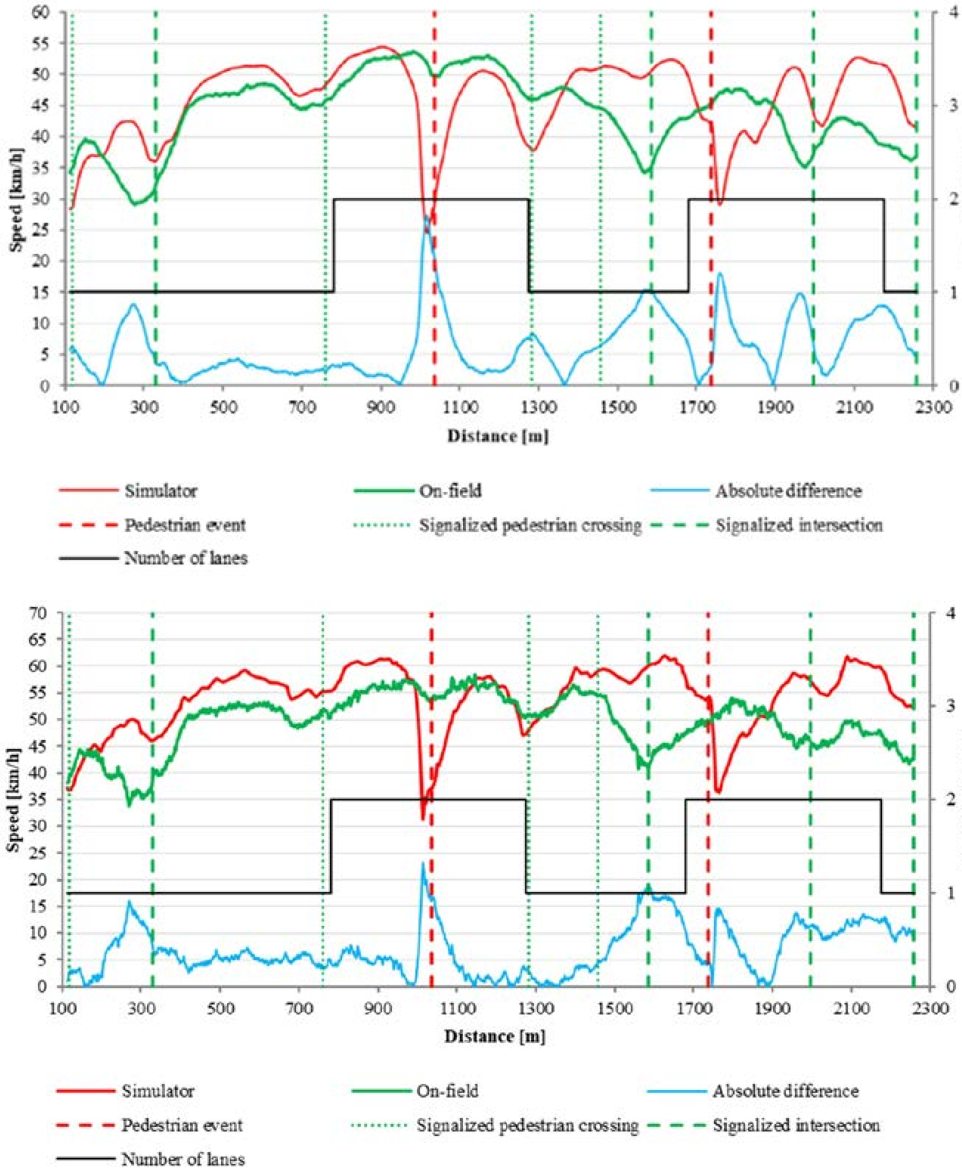

Fig. 5: speed profile comparison (above: average, below: V85)

The trend of the two profiles is similar. However, there are some areas where differences between the two profiles are noticeable. Regarding the simulator tests, the pedestrian who is crossing the street should be mentioned. This event obviously affected drivers' speed and caused significant deceleration, thus influencing the results obtained in virtual reality experimentation. This explains the negative peaks of the average profile in virtual reality (dashed red lines). On the other hand, as far as the field tests are concerned, it must be remembered that the traffic conditions were not restricted or imposed such as in virtual reality where all traffic lights were green. Therefore, drivers' speeds were sometimes reduced due to stationary traffic or otherwise significantly delayed by red lights. In this sense, the indication of the position of both the intersections and the pedestrian crossings are needed to better explain where this type of event could potentially occur. At the same time, information on the number of lanes can help to understand where traffic queues are most likely to occur. Figure 6 shows that in the areas where there were high levels of traffic or traffic queues a negative peak in the green curves was present. To overcome these issues, it seems more appropriate to compare the mean speed profiles only in similar traffic conditions (i.e., where the contingent conditions are the same for virtual reality and in-field tests), excluding therefore all the road segments where speed profiles are strongly affected by external conditions (i.e., pedestrian crossing the street in virtual reality tests (in red) and delays due to high traffic level in real world (in yellow)). Therefore, as shown in Figure 6, eleven (11) different segments were identified.

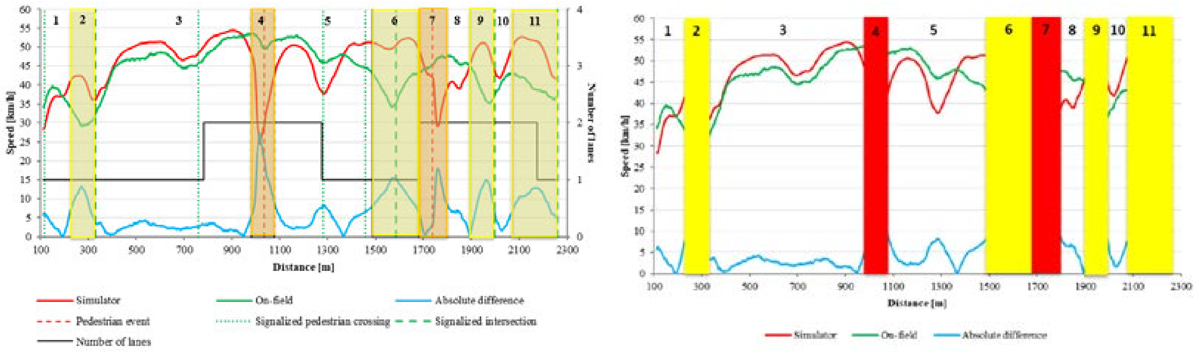

Fig. 6: identification of street segment subjected to different condition between virtual reality and real world

The 1st, 3rd, 5th, 8th, and 10th segments represent the road sections where the "contingent conditions" were the same for virtual reality and in-field tests. Thus, statistical checks of absolute validity were carried out only in these sections. The 2nd, 6th, 9th, and 11th segments represent instead the road sections where the mean speed profile for the in-field test is strongly affected by traffic conditions. These areas were highlighted in yellow. Finally, the 4th, and 7th zones describe the road sections where the mean speed profile obtained in virtual reality is strongly affected by the event where a pedestrian was crossing the street. As indicated in Domenichini et. al., (2018), the pedestrian starts crossing when the vehicle was at a stopping distance from the pedestrian crossing axes (equal about 55 meters). Therefore, the influence of the event begins 55 meters before the event takes place. The end of the influenced area was assumed equal to the one assumed in the previously mentioned study, e.g., in the point at which drivers, after braking because of the pedestrian crossing, recognize that they have regained an adequate driving speed by significantly easing the pressure on the accelerator pedal to a minimum and constant value. These areas are highlighted with a red box.

The preliminary analysis shows a relative validity of the virtual reality analysis, but obviously only where the conditions in virtual reality and in real world were the same (e.g., not strongly affected by the traffic or other events).

3.2 Absolute validity

The absolute validity was evaluated only in the road segments where the same conditions were present (1, 3, 5, 8 and 10). Therefore, segments highlighted in yellow and in red were not considered in the statistical analysis (see Figure 6). Statistical analyses were carried out considering the speed values recorded in the virtual reality and on-fields tests for a given point in the travelled path. The analysis was repeated in 50 points equally spaced out (approximately every 30 m). In Table 3 the results obtained are summarized.

Table 3: statistical test results

Distance (m)	Shapiro-Wilk's test: Virtual reality	Shapiro-Wilk's test: On-field	Levene's test	t-value	t-Student p-value	d-Cohen	U Mann Whithney p-value	Results
112.0	**0.84**	**0.836**	<0.001	-3.941	<0.001	0.751	-	H0 rejected
141.5	0.019	**0.946**	**0.191**	-3.115	0.001	0.751	<0.001	H0 rejected
170.5	0.03	**0.635**	**0.072**	-1.47	**0.146**	-	**0.079**	H0 accepted
200.0	0.019	**0.738**	**0.112**	0.591	**0.556**	-	**0.813**	H0 accepted
229.0	0.01	**0.815**	**0.886**	4.957	<0.001	1.195	<0.001	H0 rejected
329.0	0.049	**0.303**	0.003	2.076	0.041	0.431	**0.178**	H0 accepted

358.5	**0.126**	0.006	0.004	2.032	0.046	0.398	**0.185**	H0 accepted
388.5	**0.523**	**0.101**	0.003	0.589	**0.558**	-	-	H0 accepted
418.0	0.043	**0.148**	**0.123**	0.887	**0.378**	-	**0.546**	H0 accepted
447.5	**0.130**	**0.138**	**0.211**	1.624	**0.109**	-	-	H0 accepted
477.0	**0.305**	**0.481**	**0.098**	1.981	**0.051**	-	-	H0 accepted
507.0	0.014	**0.859**	0.025	2.78	0.007	0.579	0.024	H0 rejected
536.5	0.006	**0.198**	0.042	3.154	0.002	0.656	0.01	H0 rejected
566.0	0.021	**0.158**	0.014	2.435	0.017	0.494	**0.095**	H0 accepted
596.0	0.005	**0.446**	0.007	2.237	0.028	0.439	**0.178**	H0 accepted
625.5	0.015	**0.081**	0.004	2.018	0.047	0.394	**0.224**	H0 accepted
655.0	0.008	**0.234**	0.006	1.743	**0.085**	-	**0.327**	H0 accepted
684.5	**0.331**	**0.586**	0.008	1.462	**0.148**	-	-	H0 accepted
714.5	**0.102**	**0.716**	0.044	1.638	**0.106**	-	-	H0 accepted
744.0	0.027	**0.402**	0.214	1.494	**0.139**	-	**0.301**	H0 accepted
773.5	0.003	**0.244**	0.175	1.943	**0.056**	-	**0.140**	H0 accepted
803.0	<0.001	**0.578**	0.048	2.433	0.017	0.500	**0.064**	H0 accepted
833.0	0.008	0.015	0.006	2.339	0.022	0.456	0.049	H0 rejected
862.5	**0.109**	**0.245**	0.002	1.438	0.155	-	-	H0 accepted
892.0	**0.053**	**0.434**	0.005	1.400	0.166	-	-	H0 accepted
921.5	**0.064**	**0.273**	0.006	1.109	0.271	-	-	H0 accepted
951.5	**0.073**	**0.780**	<0.001	-0.419	0.676	-	-	H0 accepted
981.0	**0.716**	**0.771**	<0.001	-3.833	<0.001	0.73	-	H0 rejected

1077.0	**0.631**	0.037	**0.06**	-8.423	<0.001	2.005	<0.001	H0 rejected
1108.5	**0.216**	0.02	**0.163**	-3.442	<0.001	0.819	0.039	H0 rejected
1140.0	**0.168**	0.004	0.048	-2.075	0.041	0.433	0.029	H0 rejected
1171.0	**0.393**	0.011	0.009	-2.075	0.041	0.422	0.042	H0 rejected
1202.5	**0.111**	**0.258**	0.015	-1.702	**0.093**	-	-	H0 accepted
1234.0	**0.805**	**0.969**	0.011	-2.563	0.012	0.519	-	H0 rejected
1265.5	**0.488**	**0.299**	<0.001	-4.871	<0.001	0.970	-	H0 rejected
1297.0	0.021	**0.878**	0.001	-4.966	<0.001	1.017	<0.001	H0 rejected
1328.5	0.0364	**0.133**	0.031	-2.99	0.004	0.619	0.007	H0 rejected
1359.5	**0.551**	**0.132**	**0.12**	-0.528	**0.599**		-	H0 accepted
1391.0	**0.363**	0.005	**0.433**	1.925	**0.058**		**0.084**	H0 accepted
1422.5	**0.722**	**0.054**	**0.371**	2.87	0.005	0.683	-	H0 rejected
1454.0	**0.299**	<0.001	**0.444**	3.369	0.001	0.802	<0.001	H0 rejected
1485.5	**0.534**	0.027	**0.280**	4.250	<0.001	1.011	<0.001	H0 rejected
1799.0	**0.058**	0.007	**0.741**	-6.624	<0.001	1.577	<0.001	H0 rejected
1831.5	**0.181**	0.007	0.004	-4.413	<0.001	0.860	<0.001	H0 rejected
1863.5	**0.232**	0.029	<0.001	-3.064	0.003	0.607	0.012	H0 rejected
1896.0	**0.118**	**0.865**	**0.319**	0.319	**0.751**	-	-	H0 accepted
1996.0	**0.060**	0.031	**0.207**	2.785	0.007	0.663	0.021	H0 rejected
2022.5	0.004	**0.244**	<0.001	1.022	**0.310**	-	**0.948**	H0 accepted
2048.5	0.021	0.004	<0.001	2.058	0.043	0.401	**0.140**	H0 accepted
2075.0	0.036	**0.410**	0.043	4.538	<0.001	0.944	<0.001	H0 rejected

Note: boldface indicates statistically significant values with 5% level of significance.

The results in terms of p-value were also depicted in Figure 7. The check describes the result each 0.5 m (for the considered road segment). In blue the segments where the H0 was accepted, that indicate the absolute validity. In grey the opposite result. Where the curve trends were similar, a relative validity can be found, but the absolute validity sometimes is not obtained. However, only the segments close to those strongly affected by traffic (in real world) or events where the pedestrian crosses the street (in virtual reality) present different curve trends and therefore, different drivers' behavior (H0 rejected).

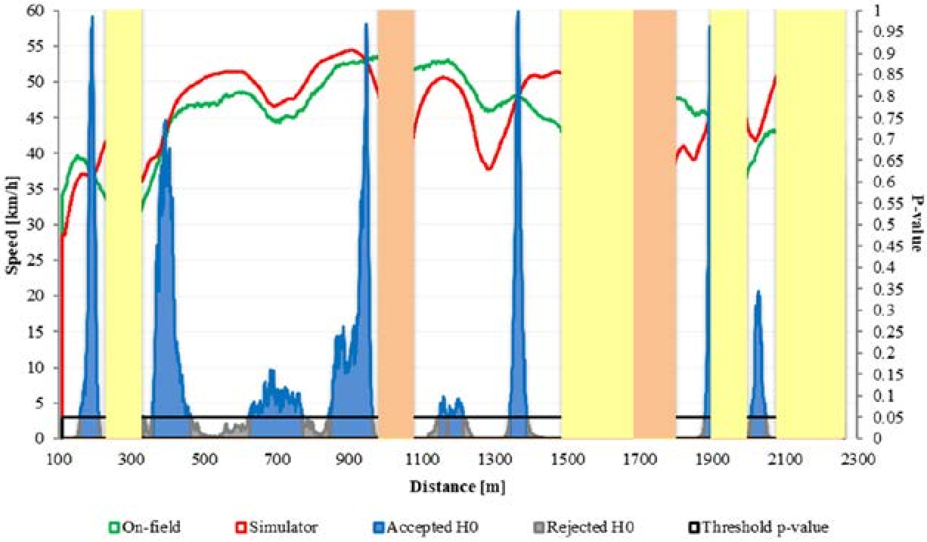

Fig. 7: results of the statistical analysis (p-value estimated each 0.5 m)

Absolute validity was also found in the road segment where a traffic calming measure is present, e.g., around a distance equal to 350 m, 700 m and 900 m where raised intersection, chicane and lane narrowing and raised pedestrian crossing are respectively present. Therefore, the virtual reality study allows to obtain a good description of the drivers' behavior, also in presence of safety countermeasures, partially confirming the finding described by Branzi et al., 2017 with reference to the street before the reconfiguration intervention (i.e., without traffic calming measures). The absolute validity was demonstrated in more than 50% of the entire road segment analyzed.

3.3 Regression analysis for validity

Finally, the regression analysis has been carried out. Figure 11 shows the regression result of the overall street. Table 4 shows instead the R^2 values obtained analyzing segment by segment, as in the previous paragraph. A good correlation among the speed values recorded during the two experimentations was highlighted in segment n.3. Lower R^2 values were instead determined in the other areas.

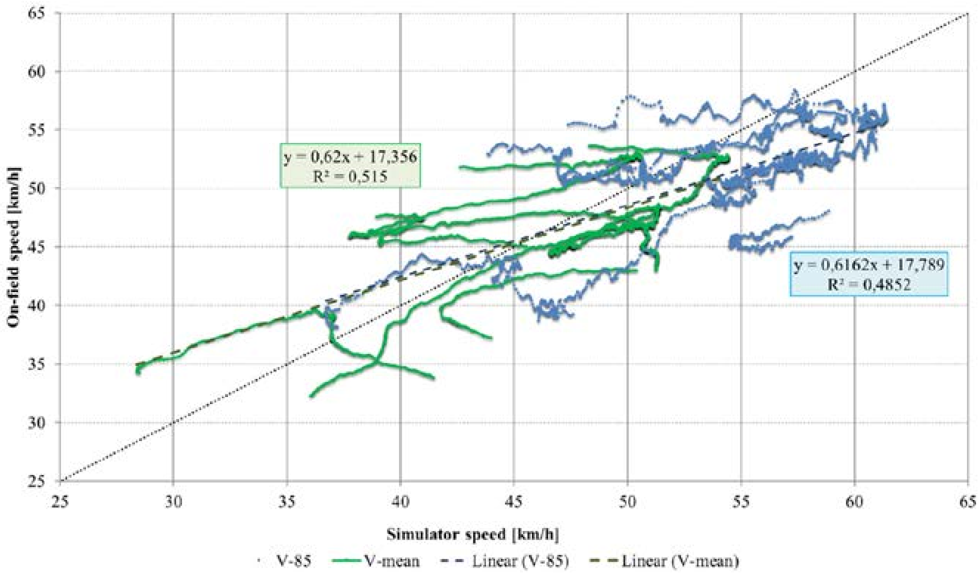

Fig. 11: regression analysis for validity (average speed and V85 speed) – overall path

Table 4: R^2 results – regression procedure for validity

Segment ID	R^2	
	Average speed	V85
1	0.0004	0.0080
3	0.8881	0.9124
5	0.0306	0.3976
8	0.1358	0.5034
10	0.6451	0.3616

The regression analysis showed very good correlation in the segments n. 3. Low values of R^2 were instead found in the other segments. The overall result showed R^2 close to 0.5 both for the average and V85 speed. The result obtained confirmed those obtained in the statistical analysis. It demonstrates also that close to the road segments interested by different "contingent conditions" the validity of the simulation can be only relative or null.

4. CONCLUSION

The analysis conducted allows to observe that drivers' behavior in virtual reality generally differs from the driver behavior in real world due, firstly, to traffic conditions and, secondly, to the different "stimuli's' perception" due to the fidelity of the driving simulator environment. The research conducted has demonstrated that events such as pedestrian crossing the street in driving simulator experimentation or real traffic conditions strongly affected the drivers' behavior. Therefore, to compare virtual reality and on-site experimentation, the same "events" and "traffic conditions" are needed.

The analysis conducted in virtual reality was evaluated both in terms of relative and absolute validity through a statistical test conducted on the entire road stretch observed and interested by different traffic calming measures. In the end also a regression analysis was made to confirm the result obtained. The two average speed profiles (obtained by virtual reality and on-field tests) presented a similar trend, maximum and minimum speed were reached in the same section if the "contingent conditions" of the experimentation were the same. In this sense, the qualitative analysis of the speed profile allows to define the relative validity of the simulation. Moreover, absolute validity was demonstrated in more than 50% of the road section analyzed. Therefore, the analysis conducted allows to demonstrate that the driving simulator study can be relevant to analyze the effectiveness of safety treatments before their implementation on real road. Moreover, this type of analysis allows the road engineering and Road Authorities to select the best engineering treatment as a function of the objective of the intervention.

It can be concluded that the LaSIS driving simulator can be considered as a valid research tool for studying the factors affecting the drivers' behavior and the effectiveness of the different traffic calming measures, confirming also the results obtained in previous research, when the same street was analyzed before the implementation of the safety intervention. The research highlights also the need to check in the "conditions evaluated" that can be quite different in virtual reality and on-field and affect the real drivers' behavior.

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ASSESSING IMPACTS OF IMMERSIVE VIRTUAL REALITY BASED DESIGN REVIEWS ON LEARNERS' SELF-EFFICACY

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ABSTRACT: *An effective design review is critical to identifying changes and/or errors at the early stage of construction projects and reduce the project costs. Traditionally, design reviews are conducted by reviewing the project by reading multiple drawings. The inherent demands of reading project drawings are especially challenging for entry-level built environment learners who often need professional experience and may need more training and skills to fully understand technical representations. Previous research has focused on evaluating the impacts of interactive visualization technologies, such as virtual reality, on the learners' design review thinking skills and showed how such technologies could support learners and industry professionals in performing design reviews. However, such research has yet to assess its impacts on their self-efficacy in engaging in design review thinking skills. Self-efficacy can be defined as one's perception of their ability to perform a task, such as problem-solving and evaluation. To understand how the VR technology can support learners in increasing their self-efficacy in performing design reviews, the researchers hosted a pilot study to evaluate immersive virtual reality design reviews' impacts. Based on the results of this pilot study, the implementation of immersive virtual reality has the potential to positively impact first year-built environment learners' self-efficacy in performing design reviews.*

KEYWORDS: *Virtual Reality, Self-Efficacy, Motivation, Education, Built Environment, Design Review*

1. INTRODUCTION

Experimental learning through hand-on experience is key for the student to gain sufficient knowledge and skills about construction and built environment subjects. However, traditional teaching, which takes place in confined classrooms with occasional aid of online or web-based learning material (Fadol et al. 2018), cannot provide students with such experience. Inaccessibility to construction sites is a main challenge for experimental learning in the construction and built environment field (Ogunseiju et al. 2021). Over the past years, educators strived to use educational technologies to enhance the learning experience of the students. Virtual reality is one of these technologies that has drawn the attention of educators in different fields such as medicine (Duarte et al. 2020), Chemistry (Kader et al. 2020), and art (Serafin et al. 2016). Compared with traditional teaching, training using VR can stimulate students' interest in learning, and promote students' active learning while saving teaching costs and avoiding safety risks (Ding and Li 2022). VR-based learning can improve self-efficacy and motivation of the learners as it allows students to interact with a virtual environment resembling the actual environment and make experiments in a risk-free environment. Past studies showed the effectiveness of VR technologies for teaching different subjects in the Architecture, Engineering and Construction (AEC) industry such as infrastructure management (Arif 2021), earthquake-resistant construction (Kuncoro et al. 2023), offsite construction (Goulding et al. 2012) and safety (Le et al. 2015) (Le et al. 2014).

Design review is one of the critical tasks in the AEC industry because identification of design changes and/or errors at the early stage of construction projects can significantly reduce the project costs. This task requires the participation of various stakeholders and interpretation of multiple engineering drawings, which is often challenging for entry-level built environment learners who do not have professional experience. Therefore, they need training to fully understand technical representations in the drawings and gain pertinent skills in design review. VR-based learning has been used effectively for educating students in design review and enhance their thinking skills (Kandi et al. 2020). However, no research has assessed the impact of this approach on the self-efficacy of learners and engaging them in design review. To bridge this gap, this research aims to understand and evaluate how VR can support learners in increasing their self-efficacy in performing design reviews. To this end, a pilot study was conducted with students at the undergraduate level for teaching design review practices. The

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Fadi Castronovo, Seyedreza Razavialavi, Abdullahi Abdulrahman, Mohammed Rayan Saiba, Pablo Martinez Rodriguez, *Assessing Impacts of Immersive Virtual Reality-Based Design Reviews on Learners' Self-Efficacy,* pp. 219-230, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.21

results of the study were then analysed, and the limitations of the research along with directions for future research are presented.

2. LITERATURE REVIEW

2.1. Immersive Virtual Reality in the Built Environment

Virtual Reality (VR) has several potential applications in many fields, including medicine, engineering, education, and entertainment (Hamad and Jia, 2022). VR could be defined as a technology that simulates an environment, which can be interacted with in a manner that appears real or tangible (Sanni Hafiz Oluwasola and Ayinde Munir 2015). The origins of VR technology can be traced back to the mid-1970s, with early experimenters using phrases like "artificial reality" to describe it (Machover and Tice 1994). The term "virtual reality" was coined by Jaron Lanier, founder of VPL Research, and the technology has since evolved from user interface design, flight and visual simulation, and telepresence technologies (Machover and Tice 1994). Freina and Ott (2015) identifies that there are two types of VR: immersive and non-immersive VR. Non-immersive VR is a computer-based environment that simulates places in the real or imagined world, while immersive VR gives the perception of being physically present in the non-physical world. Both types of VR are becoming more user-friendly and economically accessible (Kandi et al. 2020). Kaplan-Rakowski and Gruber (2019) further divided immersive VR (IVR) into low-immersion virtual environments (LiVR) and high-immersion three-dimensional spaces (HiVR). LiVR is a computer-generated three-dimensional virtual space experienced through standard audio-visual equipment, such as a desktop computer with a two-dimensional monitor. The ubiquitous online virtual world Second Life is an example of a LiVR environment. HiVR is defined as a computer-generated 360-degree virtual space that appears spatially realistic due to the high immersion afforded by a head-mounted device (Kaplan-Rakowski and Gruber 2019).

The technology has also undergone significant advancements in recent years, with new displays, input devices, and technologies being developed and introduced to the market (Anthes et al. 2016). VR has the capability to present spatial information in a more engaging manner, allowing for interaction with designed spaces at a human scale (Pacheco et al. 2014). Large screen size and wide field of view are key features of immersive VR systems, while texture, lights, shadows, and objects contribute to the overall VR experience. These VR attributes can further augment the richness of information and enhance the visualization process VR is being increasingly used in architecture, engineering, and construction to support experiential learning, movement through space and time, and interaction with the design (Sala 2013). VR enables a more qualitative representation of spaces from the users' perspective, creating the illusion of depth and immersion (Castronovo et al. 2013).

VR technology has the potential to impact the way users conventionally think and design the built environment promoting it beyond space and time constraints (Paranandi and Sarawgi 2002). The applications of the VR technology in Architecture, Engineering and Construction (AEC) industry are extensive, particularly in simulating environments and creating the feeling of immersion in a virtual world, which can assist architects and engineers in evaluating designs, understanding the needs of different users, especially those who are older or disabled. It can also promote inclusive design by providing in-depth insight into how particular groups of people experience the designed environment and how they interact with it. Nikolić and Whyte (2021) argue that VR can be used as a platform for an interdisciplinary integration of the allied design, social, and environmental disciplines. VR technology can provide easy-to-use communication solutions for all stakeholders in the AEC industry by providing a computer simulated environment with visual, auditory and haptic channels (Kähkönen 2003). VR technologies and computers are being utilized to facilitate the planning and construction of the built environment by aiding in the visualization and simulation of proposed designs, evaluating the visual impact of urban designs, and exploring broader economic ramifications (Whyte 2003). Tytarenko et al. (2023) reconstructed the Kilburun Fortress by monitoring the object's territory, analysing archival, librarian, and cartographic sources, and using various software tools such as AutoCAD, SketchUp, Quixel, and Twinmotion for modelling, rendering, and visualization. The resulting 3D model can be integrated into ArchiCAD and Revit software and showcases the applications of VR in the built environment. Although virtual reality environments (VRE) have enormous potential to engage students in classrooms and aid in construction workers' retention of safety knowledge, the adoption of VRE in the AEC industry remains minimal, as safety professionals still prefer hands-on training (Bhoir and Esmaeili 2015).

VR adoption faces several challenges in architecture and design, including a lack of integrated 3D databases and accurate reality models, technical limitations such as precise monitoring and remote sensors, and challenges in education such as the uniqueness effect, cybersickness, and accessibility (Fakahani et al. 2022). VR is also limited in its ability to create a real-life experience, particularly in conveying appropriate social behaviours and creating convincing virtual characters (Fakahani et al. 2022). Overcoming these challenges requires interdisciplinary efforts and finding the appropriate level of intervention (Fakahani et al. 2022; Hajirasouli et al. 2023; Lach et al. 2020; Zhang et al. 2020). Zhang et al. (2020) proposed future research directions on using the VR technology for the built environment, including user-centred adaptive design, attention-driven virtual reality information system, construction training system incorporating human factors, occupant-centred facility management, and industry adoption.

2.2. Immersive Virtual Reality in the Built Environment Education

Current practices in the built environment education often fall short of adequately preparing students for the complexities and challenges of real-world professional settings (Afacan 2023; Gardner 2022). Conventional teaching methods, which rely largely on textbooks and two-dimensional representations such as drawings and photographs, may fail to convey the multidimensional and dynamic nature of the built environment (Stewart and Baker, 2019). Students may therefore struggle to comprehend spatial relationships, scale, and materiality, limiting their comprehension of the built environment (Stewart and Baker, 2019). In addition, limited access to job sites and real-world initiatives hinders students' ability to gain hands-on experience and understand the practical implications of their decisions (Gibbons et al., 2021).

These limitations underscore the pressing need for innovative approaches that bridge the gap between theory and practice, equipping students with the necessary competencies to thrive in the complex-built environment. Consequently, situated learning is crucial to this field of study, as learning about the built environment requires exposure to a vast array of historical structures and design conditions (Afacan 2023) Situated learning in the built environment refers to an educational approach that emphasises learning within authentic and pertinent real-world contexts. It entails actively engaging students in tasks and challenges that replicate the complexities and requirements of their future professional roles (Bakhteyari et al., 2018; Aggerholm and Misfeldt, 2016). As a means of providing students with hands-on experience, conventional instructional methods utilise various case studies. Steele et al. (2023) assert that case studies are crucial for the education of those who are involved with the built environment. Thus, analysing completed projects allows students to examine the design process, construction techniques, and challenges faced by professionals, facilitating the development of problem-solving abilities and exposure to different design strategies (Hjaltadottir et al., 2018). However, when using case studies, the traditional teaching style encounters difficulties. To begin with, there are difficulties in comprehending projects through drawings and images, which limits students' grasp of spatial relationships, scale, and materiality (Stewart and Baker, 2019). Furthermore, limited access to job sites prevents students from firsthand experiencing the built environment, limiting their comprehension of project context and restrictions (Gibbons et al., 2021). Furthermore, student visits to construction sites are hampered by safety concerns, limiting exposure to construction processes and site-specific difficulties (Liu et al. 2019).

To address these challenges, the emergence of virtual reality (VR) technology holds promise in enhancing situated learning and overcoming the limitations of traditional methods (Elghaish et al. 2021). The advent of VR tools has enabled individuals to begin experimenting with and employing VR (Liu et al. 2019). According to Elghaish et al. (2021), VR is a revolutionary technology that has the potential to improve construction design processes as well as promote education in the built environment. VR provides an immersive platform that enables students to virtually explore case study projects in three dimensions. By experiencing projects from various perspectives, students gain a deeper understanding of spatial layout, scale, and design intent (Ho et al., 2018). VR simulations enhance visualization by offering realistic representations of projects, allowing students to interact with virtual elements and observe the dynamic behaviour of structures or building systems (Lee et al., 2020). Furthermore, VR in the built environment education can help researchers and students simulate real-life, potentially hazardous situations without exposing them to actual danger, making VR experimentations a credible approach for resolving construction clashes and defects (Afzal and Shafiq, 2021). Also, learners can efficiently investigate contextual dimensions associated with a building project using VR by adjusting specific parameters, making variable control simple to achieve (Xu and Zheng, 2020). Young et al. (2021) postulated that VR allows users to have an immersive experience of construction projects, so they can react effectively in real-world situations. Because participants in a lively, evolving situation can better try to remember safety knowledge, technological tools are also applicable in fields such as building risk assessments and safety training (Zhu and Li 2021).

Amidst the propagation of VR in the built environment, its maximum potential is yet to be realized (Safikhani et al. 2020), and there is a significant gap in VR involvement in the built environment between academia and industry (Delgado et al. 2020).

2.3. Self-Efficacy and Motivation

Self-efficacy is a belief in one's ability to perform well on a task and is a core concept of Social Cognitive Theory (Bandura 1997). Bandura (1997) indicated that self-efficacy is a key determinant of behavioural change, and psychological procedures can alter the level and strength of self-efficacy. Self-efficacy is an important factor in motivation, achievement, and accomplishment, and can be influenced by a variety of factors, including personality, motivation, and the task itself (Bandura 1997). Those with a high level of self-efficacy are not only more likely to succeed, but they are also more likely to bounce back and recover from failure (Resnick 2008).

Schunk (2011) describes how self-efficacy influences choice of activities, effort, persistence, and achievement, and how interventions involving models, goal setting, and feedback can affect self-efficacy. Eliyana et al. (2020) found that self-efficacy of entrepreneurial students influences achievement, and motivation significantly mediates the effect of self-efficacy on entrepreneurial achievement. Rodríguez et al. (2014) found that teachers with intermediate self-efficacy perception have more learning-oriented students than teachers with high self-efficacy, and students of teachers who are overconfident of their teaching capacity seem to engage less in studying to learn. Overall, self-efficacy is an important factor in motivating individuals to achieve their goals.

It is well documented that self-efficacy has a positive effect on motivation. Kanfer (1990) described motivation as the "psychological forces that determine the direction of a person's level of effort and a person's level of persistence in the face of obstacles". There are two types of motivation namely: extrinsic and intrinsic motivation (Schunk 2011). Ryan and Deci (2000) defined intrinsic motivation as the natural human propensity to learn and assimilate, while extrinsic motivation can either reflect external control or true self-regulation. Benabou and Tirole (2003) reconciles the economic view that individuals respond to incentives with the psychological view that rewards and punishments can undermine intrinsic motivation. Kuvaas et al. (2017) found that intrinsic motivation was associated with positive outcomes, while extrinsic motivation was negatively related or unrelated to positive outcomes. Overall, intrinsic motivation is driven by internal factors, while extrinsic motivation is driven by external factors, and that the two types of motivation can have different effects on outcomes.

Motivation is crucial in education and can fosters creativity and critical thinking as it cultivates resilience and self-assurance, and improves a student's agency (Schunk 2011). Motivation to learn provides direction, enthusiasm, and persistence in learning (Alfiah et al. 2021). Motivation is important for both students and teachers in achieving desired outcomes in education (Shrestha 2020). The theories of Maslow's hierarchy of needs and expectancy theory shed light on the fundamental aspects of motivation in the context of learning (Shrestha 2020). The application of various methods to motivate students and teachers is crucial and should be tailored to specific situations and requirements, as there is no universal approach (Shrestha 2020). The motivation of both teachers and students holds significance in ensuring an effective teaching and learning process within the field of education (Shrestha 2020).

Low motivation is associated with poor academic performance. Not being motivated was found to be associated with higher levels of stress and a lower Grade Point Average (Rücker 2012). Motivation is a key factor in effective school functioning and academic achievement (Halawah 2006). Fortier et al. (1995) proposed and tested a motivational model of school performance, which found that autonomous academic motivation positively influenced school performance.

Low motivation in education can be caused by various factors. Economic factors, low employment prospects, and educational background can contribute to low motivation in college students (Sahib, 2020). Intrinsic factors, such as a lack of interest in learning activities and embarrassment, can cause low motivation in elementary school students (Alfiah et al. 2021). A lack of interaction between teachers and students, as well as low reading ability, can contribute to low motivation in middle school students (Alfiah et al. 2021). O'Neil et al. (1995) found that offering financial incentives can increase student effort and improve test scores, suggesting that low motivation may be due to a lack of consequences or stakes attached to performance. Therefore, addressing factors such as economic status, interest in learning activities, teacher-student interaction, and incentives may help improve motivation in education.

Educators can increase students' motivation in the classroom by employing various strategies. Pahlavannezhad and Nejatiyan (2013) found that early knowledge of the course syllabus and assessment, rewards and positive reinforcement, and group work and role play can increase students' motivation to learn English. Brophy (2013) suggested that teachers can establish their classes as collaborative learning communities, support their students' confidence as learners, and help them appreciate curricular content as worth learning and applicable to their lives outside of school. Williams-Pierce (2011) identifies five key factors impacting student motivation: student, teacher, content, method/process, and environment, and provides suggestions from each area that can be used to motivate students. Mart (2011) suggested strategies such as providing a positive learning environment, using technology, and incorporating student interests to sustain students' classroom motivation.

Motivation has a positive impact on academic performance. Haider et al. (2015) found that both intrinsic and extrinsic motivation had a positive impact on students' academic performance. Goodman et al. (2011) found that intrinsic and extrinsic motivation were significantly related to academic performance, and that effort mediated this relationship. Afzal et al. (2010) also found that both intrinsic and extrinsic motivation had a positive impact on academic performance. Fortier et al. (1995) proposed and tested a motivational model of school performance, finding that perceived academic competence and perceived academic self-determination positively influenced autonomous academic motivation, which in turn had a positive impact on school performance. Overall, these papers suggest that motivation is an important factor in academic performance.

3. METHODOLOGY

3.1. Research Questions

As highlighted in the literature review, the implementation of immersive virtual reality (IVR) in built environment (BE) requires further research. New research efforts must investigate the impacts that the implementation of this technology has on learners' motivation, and specifically self-efficacy. Furthermore, as highlighted in section 3.2. research in the implementation of IVR in BE education necessitates investigations that leverage rigorous experimental methods. Based on this research gap, the researchers set out a goal of assessing the impacts that an IVR learning activity has on higher education learners in the BE discipline. Therefore, the research was concentrated on measuring the impacts of this activity on learners' self-efficacy and experience.

Based on these goals, the following research questions were posed:

1. Does performing design reviews with immersive virtual reality lead learners to have a higher self-efficacy?
2. Is the learners' experience positive whilst performing design reviews with immersive virtual reality?

Based on these research questions, two null hypotheses were considered. The first hypothesis was that the learners' reported average self-efficacy was going to be the same before and after the learning activity. Meanwhile, the second null hypothesis was that the learners' average experience was going to be neutral.

3.2. Experimental Design and Procedure

To test the hypotheses, the researchers designed a pilot study to test the early impacts of IVR. This pilot study was designed as a one group pre-test / post-test quasi-experiment to assess the impacts on learners' self-efficacy. This pilot study is considered a quasi-experiment due to the lack of randomized assignment to the treatment group. This method is not optimal for the generalization of the data and the impacts of the learning activity might be due to test learning. However, this method is acceptable for running pilot studies and assessing early impacts and identifying early trends (Knapp 2016).

In this pilot study the independent variable or treatment had only one level. This level was the learning activity designed to introduce first year BE learners to the concepts of design reviews while using IVR. The dependent variable measured for this pilot study was the learners' self-efficacy. The assessment instrument designed to measure the learners' self-efficacy is explained further in section 3.4. The procedure for this quasi-experiment can be seen in Figure 1. The participants were students and took part in this learning activity as part of their class time. The students had to participate in the activity; however, they were given the option not to participate in the pre and post-tests. A 10-minute pre-test was administered before the start of the activity. The same 10-minute test was administered as a post-test after the activity.

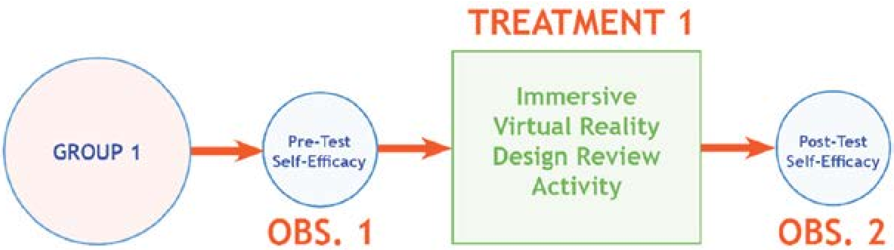

Figure 1. Quasi-experimental Procedure

After the pre-test the participants were provided with a tutorial on how to use the IVR head-mounted system. This tutorial allowed the participants to get familiar with the virtual environment and navigation controls. This tutorial lasted about 10 minutes. Participants that still had difficulty with the controls were provided with additional support and instruction. After the tutorial the participants were asked to navigate through a BIM model of a residential house and identify design mistakes. This residential house was designed in Autodesk Revit to have several design mistakes. The participants were paired in groups of two, where one was assigned the role of "driver" and the other of "note-taker". The driver would wear the headsets, which were casting its video output also to a desktop computer screen. The note-taker was tasked to write down design mistakes that the driver was identifying, on a sheet provided by the team. For every five design mistakes the participants had to switch roles. The total duration of the design review was set to be 30 minutes. This time limitation was also set to limit potential motion sickness of the participants.

3.3. Participants

The participants in the pilot study were first-year students enrolled in an Introduction to the Built Environment module at a university in the south of the United Kingdom. A total of 54 students were enrolled in the module and were asked to participate in the study. Ethical approval was received by the university ethic board to perform the study, and students were asked for consent to collect the data before administering the pre-test. As mentioned earlier, students that did not want to participate in the study were given the option of not answering the pre and post-test, but still had to participate in the class activity.

3.4. Equipment and Assessment instruments

The research team used twenty IVR headsets, the Meta Quest 2. This allowed a total of 40 students to participate in the activity. The video output of the headsets was cast on desktop computer screen over the Chrome web browser. To host the design review sessions the researchers used the IVR Arkio® software. Arkio allows users to host collocate in a virtual environment and perform design review sessions collaboratively. Learners were provided with virtual meeting rooms where the model of the residential house was preloaded.

The measured dependent variable was the participants' self-efficacy and experience. The pre-test was composed of ten questions. The questions were based on the "General Self-Efficacy Scale" (GSS) developed by Schwarzer & Jerusalem (1995). The questions from the GSS instrument were slightly changed to ask the participants about their perceived ability to perform design reviews. The post-test was composed of the same ten questions from the pre-test as well as an additional eleven questions to capture the learners' experience. These questions were based on the instrument developed by Boekaerts (2002), the OnLine Motivation Questionnaire. The participants were asked to indicate their agreement with the statements on a 5-point Likert scale. The questions for the pre and post-test can be found in Table 1.

Table 1. Pre and Post Tests Questions

Pre and Post Tests Self-Efficacy Questions	Post Test Participant Experience
1. How good do you think you are at reviewing design proposals?	11. How do you feel just after finishing the activity?
2. I am able to review most of the design proposals that I am presented with.	12. How easy was this activity?
3. When facing a difficult design proposal, I am certain that I can review it.	13. How well do you think you did in this activity?

4. In general, I think that I can successfully review most design proposals.	14. How useful do you consider this activity in learning about design reviews?
5. I believe I can succeed at reviewing most design proposals.	15. How important do you find it to do well on design reviews?
6. I am able to successfully review design proposals.	16. I felt the time used for the activity was beneficial.
7. I am confident that I can perform effectively design reviews.	17. I saw the value in the activity.
8. Compared to other people, I can do most review design proposals very well.	18. How enthusiastic were you about this activity?
9. Even when the design of a building is complex, I can review it quite well.	19. How pleasant did you find this activity?
10. How difficult did you find the topic of design reviews?	20. How much did you enjoy yourself during this activity?
	21. How much would you recommend this activity to your classmates?

4. RESULTS AND ANALYSIS

In this research, the research questions were answered by conducting two different types of statistical analyses. The first research question, which aimed to evaluate if the learning activity supported the participants in gaining higher self-efficacy, was tested by conducting a Paired-Sample T-Test. The second research question aimed at evaluating the participants' experience while participating in the activity. This question was evaluated by performing a One-Sample T-Test. This analysis aimed to test if the participants' experience was higher than neutral towards the positive. The tests were conducted using the statistics software package, IBM SPSS Statistics. A summary of the results can be found on Table 2 for the Pre and Post-Test, and on Table 3 for the participants' experience. While a total of 54 participants were recruited, only a total of 29 data points were used for the study as the rest either did not participate in activity or did not give permission to use the data.

Using the results from Table 2, a Paired-Sample T-Test was conducted to test if there was significant difference between the pre and post-test for the participants' self-efficacy. No outliers were detected that were more than 1.5 box-lengths from the edge of box in a box plot. Participants reported a higher self-efficacy after participating in the activity (3.890 ± 0.440) when compared to before the activity (3.190 ± 0.0.498), a statistically significant increase of 0.70 (95% CI, 0.885 to 0.536), $t(28) = 8.042$, $p < .0001$, $d = 1.493$. Therefore, the researchers confidently rejected the null hypothesis that the averages for the pre and post-test were going to be the same, as indicated by the significant difference and p value being below 0.0001. Furthermore, the effect size of the sample is quite large as indicated by the Cohen's D being 1.493 (Cohen 1988).

Using the results from Table 3, a One-Sample T-Test was conducted to test if the participants' experience was significantly different than neutral (Likert Scale value of 3). No outliers were detected that were more than 1.5 box-lengths from the edge of box in a box plot. The mean participants' experience score was significantly higher by 0.998 (0.95 CI, 0.7502 to 1.2205) than a neutral score of 3, $t(28) = 8.792$, $p < 0.0001$, $d = 0.606$. Therefore, the researchers confidently rejected the null hypothesis that the average for participants' experience was going to be neutral, as indicated by the significant difference and p value being below 0.0001. Furthermore, the effect size of the sample is between medium and large as indicated by the Cohen's D being 0.606 (Cohen 1988).

Table 2 – Pre and Post Test Average Answers

Question	Pre-Test Average	Post-Test Average
1. How good do you think you are at reviewing design proposals?	3.14	3.90
2. I am able to review most of the design proposals that I am presented with.	3.43	4.03
3. When facing a difficult design proposal, I am certain that I can review it.	2.90	3.79
4. In general, I think that I can successfully review most design proposals.	3.41	4.07
5. I believe I can succeed at reviewing most design proposals.	3.52	4.07
6. I am able to successfully review design proposals.	3.28	4.10
7. I am confident that I can perform effectively design reviews.	3.17	3.86

8. Compared to other people, I can do most review design proposals very well.	3.14	3.76
9. Even when the design of a building is complex, I can review it quite well.	2.97	3.69
10. How difficult did you find the topic of design reviews?	2.93	3.66
Self-Efficacy Average	3.190	3.890
Standard Deviation	0.498	0.440

Table 3 – Participants' Experience Average Answers

Question	Average
11. How do you feel just after finishing the activity?	
11.A How relieved do you feel after the activity?	3.62
11.B How at ease do you feel after the activity?	3.90
11.C How nervous do you feel after the activity?	2.97
11.D How satisfied do you feel after the activity?	4.14
11.E How worried do you feel after the activity?	3.38
11.F How confident do you feel after the activity?	3.90
11.G How concerned do you feel after the activity?	3.34
12. How easy was this activity?	3.97
13. How well do you think you did in this activity?	4.00
14. How useful do you consider this activity in learning about design reviews?	4.24
15. How important do you find it to do well on design reviews?	4.31
16. I felt the time used for the activity was beneficial.	4.31
17. I saw the value in the activity,	4.34
18. How enthusiastic were you about this activity?	4.07
19. How pleasant did you find this activity?	4.55
20. How much did you enjoy yourself during this activity?	4.45
21. How much would you recommend this activity to your classmates?	4.48
Participants' Experience Average	3.998
Standard Deviation	0.606

5. CONCLUSION

The ability to review and evaluate proposed design proposals is a key skill that BE learners must have once they graduate from their higher education institution. As discussed in the literature review, several studies have shown the positive impacts that IVR has on students' learning and their ability to meet learning objectives. However, the role of instructors is not just about meeting learning objectives, but it is also to support learners in developing their self-belief and confidence necessary to enter the industry.

This research conducted a pilot study to evaluate the effectiveness of using IVR in improving self-efficacy of students in engaging in design review thinking skills. The results and analysis have shown that, at a pilot study level, an IVR learning activity has potential in impacting students' self-efficacy while also being a positive experience. When looking at the first research question, the learning activity supported students in increasing their self-belief that they can perform design reviews while immersed in a virtual reality environment. This pilot study can give an early insight into what are the impacts that IVR has in the classroom beyond meeting learning objectives, supporting students in their confidence levels.

The next steps of this research efforts are to mitigate the limitations of sample size by recruiting a larger number of participants to support the researchers in scaling the findings and improving the generalization of the results. Additionally, one group pre-test / post-test quasi-experiments have experimental limitations and threats to internal and external validity. Therefore, the future research can include additional treatments to tackle the validity of the results. To address this limitation, the research has already started collecting the impacts a different medium, non-immersive VR, has on learners. By adding an additional treatment, a repeated-measure experiment and a two-way mixed ANOVA analysis can be conducted. To conclude, this study reports an initial result of an on-going research and the researchers will share further information on the research results in future publications.

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COGNITIVE DYNAMICS FOR CONSTRUCTION MANAGEMENT LEARNING TASKS IN MIXED REALITY ENVIRONMENTS

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ABSTRACT: *Technologies to communicate construction project information (engineering designs, schedules) have evolved into a wider range of innovative ecosystems for engineering practices (e.g., cloud-based 3D representations and advanced immersive environments). There is a lack of exploration of effective user interaction for learning and training in relation to how presented information influences cognition in these ecosystems. The presented research investigates the users' cognitive and attentional differences using the interactive capabilities of Mixed reality (MX) technology. The enhanced user-situation interactions are analyzed by measuring cognitive dynamics with an emphasis on two processes (attentional focus and cognitive load) in relation to the challenge of the engineering learning task— defined by its complexity (limited time frame for observations of the situations, number of required observations) and nature (episodic). Cognitive dynamics were measured using an electroencephalography (EEG) device that senses electrical activity in response to changing levels of cognitive stimuli via electrodes placed on the scalp. Measuring fluctuations in cognitive processing (related to the intensity of various task demands) allows associating efforts on semantic information processing for learning and training tasks (e.g., walkthroughs for safety checks in job site in MX). The approach enhances opportunities to design technology that best adapts to the user needs for engineering practices with an efficient comprehensive performance assessment.*

KEYWORDS: *Electroencephalography (EEG), Dynamics of attention, Cognitive load, Cognitive processing*

1. INTRODUCTION

Construction sites are characterized by their dynamic nature, as they are filled with a multitude of activities and potential risks. Safety in construction is a critical aspect of production activities and a major priority effort for successful implementations in construction organizations (Guo et al., 2017). Construction safety training is of the highest priority across the industry, and the use of technology intervention has facilitated such efforts (Frank Moore & Gheisari, 2019). The provision of construction safety training plays a pivotal role in cultivating a safety-oriented environment within the construction sector. Ensuring optimal safety in the construction industry necessitates a collaborative endeavor involving various stakeholders, including owners, designers, construction companies, workers, regulators, and educators (Sacks et al., 2013). Typically, prior to commencing work on a construction site, workers are mandated to complete an Occupational Safety and Health Administration (OSHA) 10-hour construction training program. This program is delivered online and encompasses safety-oriented lectures, videos, and slides.

The efficacy and significance of this training program, as well as its adequacy, are continually pertinent inquiries (Wilkins, 2011). There have been efforts focused on implementing a more effective construction safety training program using different methods like personalized training programs or training with virtual reality devices (Jeelani et al., 2020). However, VR technology implementations generate potential risks for the user. For example, they don't easily enable representing at-scale safety requirements in the VR environments for the users' own exploration in training. Another possibility of risk is that VR applied to OSHA safety training may become a new source of distractions to users (Asish et al., 2022), impacting the intended outcome of training.

Despite the widespread use of technologies in training (including VR and AR as interventions), methods that reveal the effectiveness of the technologies as training approaches are not incorporated into the training programs. For example, methodologies for assessments employ paper-based exams or supervised self-reports—which have considerable limitations— to determine subjects' performance before and after the training program (Jeelani et al., 2020). It is critical, therefore, to comprehensively assess the effectiveness of inventory training tasks with the use of technology by considering the individual characteristics of the trainee (technology user) as they factor or are subrogate into the overall performance. There is a need to find alternative methods to assess the efficacy and benefits of implementing safety training interventions due to individual differences and self-report methods' disadvantages—ranging from response bias, recall bias, and subjectivity to cultural and language barriers. The researchers anticipate that incorporating the users' individual performance front and center might facilitate a smooth path to successful training programs.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Xuanchang Liu, Ivan Mutis, *Cognitive Dynamics for Construction Management Learning Tasks in Mixed Reality Environments,* pp. 231-241, DOI 10.36253/979-12-215-0289-3.22

The presented work uses Mixed Reality (MX) technologies. MX combines real and virtual worlds for the creation of environments where users can function and interact in the physical and virtual worlds. MX has facilitated the consolidation and analysis of activities in the physical space, such as in production processes involved in the manufacturing of goods or services—i.e., the activities for converting raw materials into finished products. The co-existing of real and virtual interaction allows connections and reactions between virtual objects and the physical space, undoubtedly facilitating the enhancement of the study of construction activities, including training programs in the industry. For example, by "moving" the construction site production activities into just a small physical space for training.

This study presents a novel assessment method utilizing electroencephalography (EEG) technology. The EEG is used to measure electrical activity in the brain, which output data brings insights into the timing and nature (rhythms in brain activity across frequency bands— delta, theta, alpha, beta, and gamma) of the underlying cognitive processes. The presented research proposes the utilization of the EEG technique for safety training and problem-solving tasks. The method enables the automatic collection of data from individual trainees to study the effectiveness of training tasks. The approach collects the neural response when learners attempt to address challenges in training tasks under conditions of complexity, such as the cognitive effort involved in solving a question. By conducting an analysis of the EEG data, this technique provides information to assess the training or problem-solving tasks through cognitive load and attention degree analysis for individuals, providing information on which task the user performs well or has deficits. The outcome can easily correlate to individual differences (cognitive abilities such as memory, attention, perception, and problem-solving skills) to find the effectiveness of the overall training tasks. For example, what is the impact of attention deficits on particular training tasks?

The presented study focuses on the problem-solving process in order to develop a more effective, precise, and unbiased approach to assessing performance in training.

2. BACKGROUND

Since the early 20th century, scientific studies using electroencephalography techniques have experienced a considerable evolution. Mainly these efforts involve the detection and analysis of minuscule electrical signals emanating from the human brain during its various activities (Sanei & Chambers, 2007). Electroencephalogram (EEG) signals are categorized into distinct power bands corresponding to various brain wave frequencies, facilitating the identification of different states or conditions of ongoing brain activity in humans (see Table 1) (Fernandez Rojas et al., 2020; Klimesch, 1999; Zietsch et al., 2007).

Table 1: Frequency and statements of brain waves.

Brain Waves	Frequency (Hz)	Statement
Delta	0.5-4	Idling and sleep
Theta	4-8	Mental fatigue and mental workload
Alpha	8-13	Mental workload, cognitive fatigue, and attention or alertness
Beta	13-30	Visual attention, short-term memory, and working memory

The literature has established the meaning of spectral powers of various EEG waves and cortical locations in evaluating cognitive load during problem-solving tasks. Researchers observed an increase in the power of both theta and alpha bands as task difficulty escalated, suggesting a direct association between these bands and cognitive load (Sarailoo et al., 2022). More specifically, the augmentation of theta spectral power serves as an indicator not only of heightened task complexity but also of enhanced working memory capacity (Borghini et al., 2012). Additionally, the beta band can potentially serve as another indicator of cognitive load and working memory during tasks. In visual working memory tasks, there has been an observed augmentation in beta activity within the parieto-occipital channels (Mapelli & Özkurt, 2019).

Building on early definitions of attention from William James, in his book *the Principle of Psychology*, James states that attention "is the taking possession by the mind, in clear, and vivid form, of one out of what seems several simultaneously possible objects or trains of thought."(James, 1890). As a condition of selective awareness, attention degree controls the quality of one's task-solving. Enhancing one's ability to regulate attention pertains to the domain of executive attention, also known as controlled attention. This cognitive process encompasses functions such as planning, decision-making, and problem-solving (Fernandez-Duque et al., 2000). Executive attention refers to the cognitive ability to deliberately redirect one's focus from one task to another or to inhibit the processing of extraneous information. This study focuses on the focus degree, as known as the intensive of attention, as one of the layers of information that help with analyzing performance. To indicate the state of attention degree, delta, theta, and alpha waves are the most used (Kaushik et al., 2022).

Multiple studies have documented an elevation in mid-frontal theta activity, a reduction in central and parietal delta activity, and a decrease in frontal and parietal alpha power during states of attention (Kaushik et al., 2022). Additionally, the relative magnitudes of spectral power across various waveforms can serve as an indicator of attention levels. As per the findings of the researchers, the attention ratio, referred to as the theta/beta ratio, possesses significant utility as an indicator for the analysis of attention. Moreover, it has been demonstrated by researchers that a robust association exists between attentional degree and the ratios of theta/beta, theta/alpha, and alpha/beta (Derbali & Frasson, 2011; Ghasemy et al., 2019; Hillard et al., 2013). More specifically, a larger ratio of alpha/beta indicates a more concentrated situation, in the meantime, there is a negative correlation between the ratio of theta/beta and the focus degree (Derbali & Frasson, 2011).

While EEG is commonly associated with medical and neuroscience applications, it also has some interesting and potential applications in the field of construction. Applications like worker cognitive load or stress level monitoring could help to improve construction on-site workers' health, well-being, and productivity (Jebelli et al., 2018; Saedi et al., 2022). The productivity of construction workers is not solely determined by their individual workload but is also greatly impacted by their emotional state, particularly when encountering hazardous work conditions or confined spaces. The utilization of wearable EEG headsets for monitoring the emotional state of on-site construction workers is a potential avenue for construction managers to enhance control and optimize the overall workflow of building projects (Hwang et al., 2018).

Given that construction workers consistently operate under conditions of high stress and heavy workloads, the matter of safety is a critical domain that researchers seek to enhance. The studies on the EEG in the construction site may lead to the optimization of the construction safety programs. For example, assessing the on-site worker's mental workload via EEG could help managers identify individuals who are not in their best mental status and better arrange human resources to reduce risk and hazards (Chen et al., 2016). On the other hand, ensuring that personnel remain focused on their hazardous tasks and that they are not easily distracted by external factors is consistently crucial. Wearable EEG devices promise to identify factors of distractions of construction workers in hazardous tasks and to improve construction site safety (Ke et al., 2021).

In addition to calls for its application in on-site construction workers, EEG has been utilized in laboratory studies based on virtual reality (VR) to enhance the performance of building or construction environments. The utilization of virtual environments offers a valuable opportunity to replicate real-world scenarios. By incorporating EEG band power scalp mapping into machine learning models, it becomes possible to assess the authentic responses of individuals residing in a building space. This analysis can encompass several aspects, such as comfort, pathfinding, and spatial utilization (Zou & Ergan, 2023). Beyond the analysis of the fatigue level from EEG signals collected in the virtual environment, collected EEG data can help the development of new models to improve the prediction and prevention of construction fall hazards (Tehrani et al., 2022).

3. METHODOLOGY

The presented approach is a model for the performance and assessment of individual trainees' problem-solving tasks implemented in an MX environment combined with an EEG headset. The MX environment will provide a virtual simulation of the training tasks, and the EEG headset will collect EEG signals for cognitive analysis on the problem-solving task. This research work employs the Theta (4-8Hz), Alpha (8-13Hz), and Beta (13-30Hz) frequency bands primarily to assess the cognitive load and attention levels exhibited during a problem-solving task.

Subsequently, the provision of performance feedback entails the comprehensive processing of all collected data. The flow of the feedback methodology process is presented in Fig.1. Detailed steps will be discussed in the following sections.

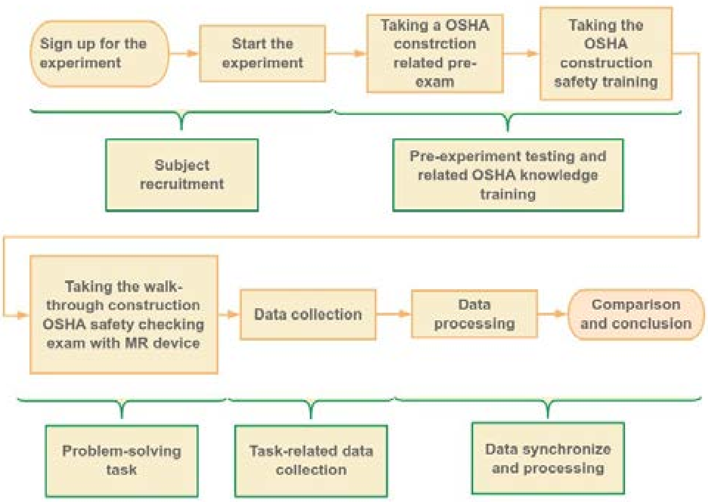

Fig.1: Workflow of the problem-solving task performance feedback process.

3.1 Subjects' recruitment and OSHA safety training

The experiments involve recruiting a sample of fifty individuals aged between 18 and 35 years old, who are enrolled in a university program with a background in civil and construction engineering. The experimental procedure will be conducted within a laboratory area measuring 5 meters by 5 meters.

Upon enrollment in the experiment, participants are required to respond to a pre-test that will inform the knowledge of OSHA construction safety training. After the pre-test, subjects are required to watch the OSHA construction safety training video and then take the OSHA construction safety examination in a virtual environment after becoming familiar with the manipulation of the MX device.

The OSHA construction safety training video refers to the selected OSHA construction regulations (Huang et al., 2003; "Top 10 Most Frequently Cited Standards | Occupational Safety and Health Administration,"). Fig. 2 is an example of the applied OSHA construction standard.

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When scaffold platforms are more than 2 feet (0.6 m) above or below a point of access, portable ladders, hook-on ladders, attachable ladders, stair towers (scaffold stairways/towers), stairway-type ladders (such as ladder stands), ramps, walkways, integral prefabricated scaffold access, or direct access from another scaffold, structure, personnel hoist, or similar surface shall be used. Crossbraces shall not be used as a means of access.

Fig.2: Example of an OSHA Construction Safety standard applied in this study.

The current approach classified the selected construction OSHA standards for violation identification in the MX environment scene into three tiers. The tiers are designed based on the complexity of violation identification, meaning the user's level of effort required—i.e., the complexity is related to the steps to determine the violation in a virtual scene. Table 2 presents the details of complexity tiers for violation of OSHA standard identification.

Table 2: Tiers and level of effort on OSHA standard violation identification in the virtual scene.

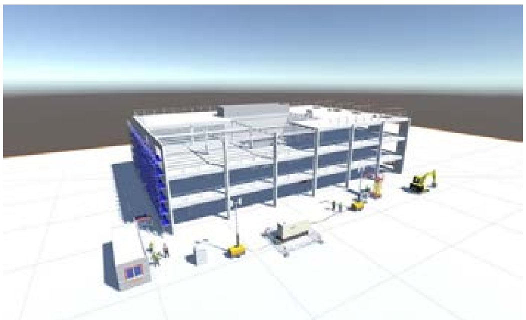
Tiers	Level of effort based on complexity of tasks for violation identification
Tier 1	Direct visual contact with the objects.
Tier 2	Need to search for information to infer a violation.
Tier 3	Need to perform actions in to determine violations

Tier 1 is applied to those violations that can be perceived through direct observation in scenes within the MX environment—i.e., there is minimum learner's effort to perceive the visualizations (visual representations) that produce the stimulus for the learners' identification of the violations. Within this tier, most of the violations could be identified by just a single observation of the virtual objects (visual representations). Typical examples for this tier are conditions that represent personal protection equipment through virtual objects (i.e., visual representation of the worker without properly using protection equipment). Tier 2 is for conditions in the scene that demand the user to search for information to infer the violations. The learners' search for information is possible by triggering actions in the MX environment. The learner's action for information search serves as an additional mediation mechanism for inference to determine violation (e.g., the learners' virtual rotation of an extinguisher in the MX scene to determine the expiration date). Tier 3 complexity consists of additional actions for inference using virtual instruments to determine violations. Using instruments for inference implies an additional level of complexity, as other cognitive capabilities (spatial and reasoning abilities) are required to determine violation (e.g., displacing instruments to measure distances in the virtual space). An example of Tier 3 is the learner's required action of using an instrument to calculate the distance that informs whether it's a violation or not (e.g., the placement of a straight ladder against a wall).

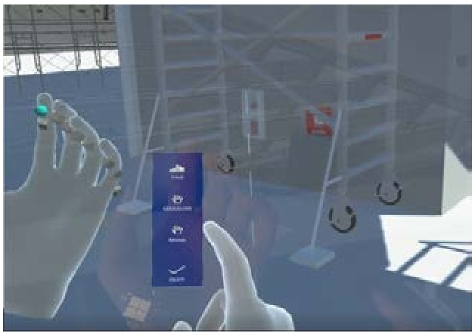
3.2 Problem-solving task design in the MX environment

The design consists of creating an examination of on-site construction OSHA safety checks. The examination is framed as a problem-solving task to draw boundaries of complexity in the search space— the possible configurations, number parameters, and elements in the MX environment that impact the users' decisions and courses of action.

Users (learners, trainees) are required to review the compliance of safety standards of construction of small commercial buildings (3 stories distributed over 40,000 Sq ft) as a project engineer from a local subcontractor company. While wearing the MX device (Hololens 2), users are asked to inspect and label safety standards violations in the first story of the building within 10 minutes. Fig. 3(a) shows the MX ongoing construction site prototype. Fig. 3(b) shows a scene where the user is required to use an additional instrument within the MX environment to determine a violation, like the measuring tape within the problem-solving task.



(a) Virtual construction site.



(b) Integrated virtual commands for labeling virtual objects.

Fig. 3. Virtual environment for OSHA training.

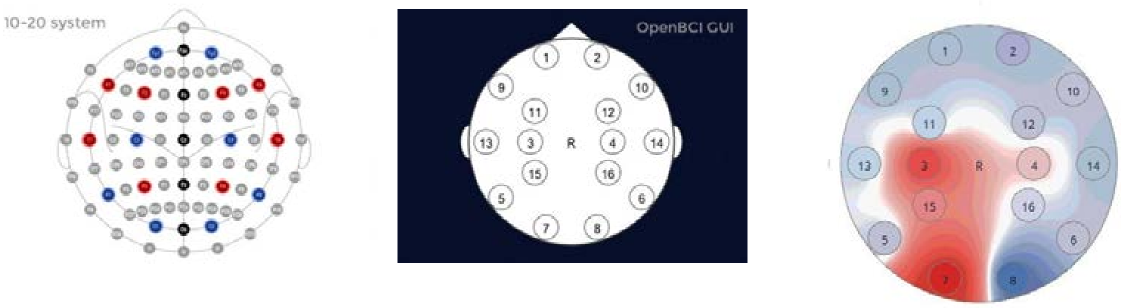
In order to facilitate unrestricted exploration of the entire construction site within a virtual environment, a navigation system was devised to enable virtual movements in the virtual world based on physical displacement in the real world (laboratory space). The navigation system allows unconstraint virtual displacements in the MX environment. Due to the constraints on mobility in the physical environment, individuals are required to physically traverse the laboratory area in order to investigate and examine the construction site comprehensively. Instead of taking the examination totally virtually like a video game, this paper is trying to configure a balance between virtual and reality through this navigation system.

3.3 Data collection

The experiment design includes the collection of video, audio, and EEG data from a MX device and an EEG headset (see Fig.4(a) and 4(b)). The EEG data is collected from an OpenBCI Mark IV headset with a sampling rate of 125 Hz. The OpenBCI Mark IV headset includes 16 channels (with additional reference and ground electrodes in A1 and A2) placed on the subject's scalp according to the international 10-20 system. This paper collects EEG signals by using all 16 channels (FP1, FP2, F3, F4, F7, F8, C3, C4, T7, T8, P3, P4, P7, P8, O1, and O2) as presented in Figs. 5(a), 5(b), and 5(c) (Homan et al., 1987; "Ultracortex Mark IV | OpenBCI Documentation,").

(a) Mixed-reality and EEG device. (b) Subject wearing the combined headset.

Fig. 4: MX with an EEG device integration.



(a) Used channels in 10-20 system. (b) Channels numbering. (c) EEG heat map while example subject ongoing data collection.

Fig. 5: Map of electrodes used in this paper's EEG data collection process ("Ultracortex Mark IV | OpenBCI Documentation,"), and heat map example for EEG signal processing.

During the implementation of the OSHA construction safety inspection, the researchers collect video, audio, and information on tagged violations by the subjects. All tagged violations will include the real timestamp information, which could help with synchronizing time stamps across different data streams and activities in the MX environment.

3.4 Post-processing

A synchronization task follows. It consists of mapping the generated streams of data collected during the experiment with the real-time stamps associated with each technology device. The timestamps were used to identify the exact occurrence of violations during the experiments. Once violation occurrences are identified, the EEG data will be segmented into 20-second epochs for target sections (20 seconds before each incident violation was labeled or tagged). The researchers post-process EEG data in MATLAB (version 2023a) and the EEGLab toolbox (Delorme & Makeig, 2004). After importing raw EEG data and electrodes' locations correspondingly, a FIR filter is applied to bandpass filter the EEG data to a frequency of 0.5-30 Hz to help to remove low-frequency drifts and power line noise. Artifacts from eye blinks and muscle movement were corrected by applying ICA in EEGLab (Winkler et al., 2014).

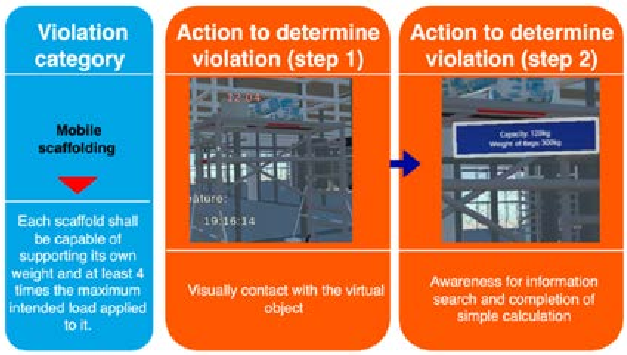
The next steps are the extraction of features of theta (4–8Hz), alpha (8–13Hz), and beta (13–30Hz) to analyze and compare the mental cognitive load and attention degree across different levels of efforts.

4. EXAMPLE OF DATA RESULTS AND DISCUSSION

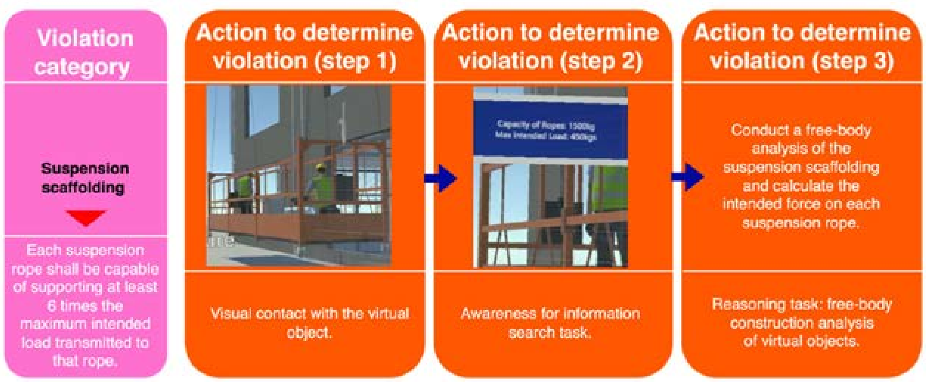
The current experimentations of the treatment and control groups are in progress. The following is an example of the typical experiment and data captured for one subject, including the data processing outcomes for the treatment group.

The presented example shows an experiment with a subject of the treatment group who has never taken any OSHA construction safety-related training. The researchers asked the subject to take a personalized OSHA safety training session. Once the training session was finalized, the researchers asked the subject to be immersed in an MX reality ecosystem by wearing the MX and EEG devices. The immersive environment consists of a virtual construction site with multiple scenes and situations that present safety violations and hazardous conditions based on OSHA standards. Each violation fell into three different tiers of complexity. As an illustration, the violations' type and complexity tier are presented in Fig. 6.

(a) Easy-level complexity violations.



(b) Mid-level complexity violations.

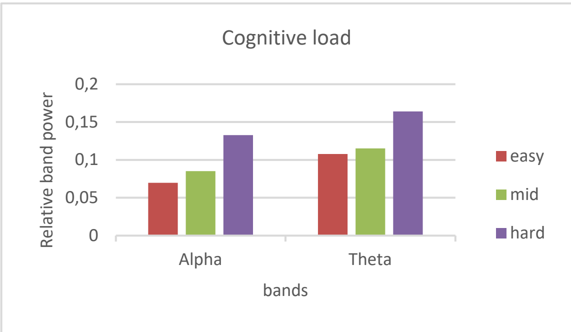


(c) Hard-level complexity violations.

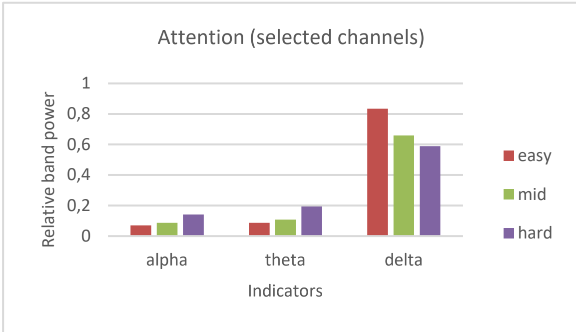
Fig. 6. Example of complexity tier violations used in the experiment.

The easy-level complexity violations (like PPE violations) would only require subjects to visually be in contact with the virtual object to check and determine the violation. For mid-level complexity violations (like mobile scaffolding capacity violation), the subject needs first to be in contact with the virtual object (as a target virtual object with potential violation)—next, the subject searches for information to make inferences and verify a violation. For hard-level complexity violations (like suspension scaffolding capacity violations), the subject requires not only the awareness of an information search task to deduce a violation but also be involved in a reasoning task. The reasoning task demands constructs a free-body analysis of virtual objects.

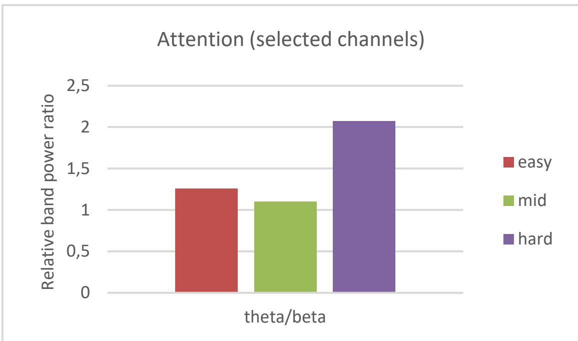
Fig. 7 (a) shows the result of cognitive load when the subject was experiencing different efforts associated with the tiers of complexity violations. As introduced in the previous sections, to analyze the cognitive load, the relative band power of Alpha and Theta was computed (Sarailoo et al., 2022). Based on the result, it can be concluded that to address the increasing complexity of tasks, individuals are required to exert a higher cognitive load to arrive at a solution. Furthermore, since the subject's cognitive load increased with the higher complexity levels when solving a task, it is possible to determine the dynamics of success and failure of each subject (cognitive dynamics of each subject). The dynamic enables the research to correlate the efficiency of the technology for training and individual differences in training tasks.



(d) Cognitive load.



(e) Attention degree (alpha, theta, and delta band).



(f) Attention degree (ratio between theta and beta).

Fig. 7. Data from cognitive processes from one subject involved in MX training task.

To analyze the attention degree when subjects address solutions in problem-solving, the band power of mid-frontal theta, central and parietal delta, and frontal and parietal alpha were computed. Besides, the ratio between theta and beta was also included as an indicator (Derbali & Frasson, 2011; Kaushik et al., 2022). As presented in Fig. 7 (b) (c), with the increase of the task complexity, the related power band of the mid-frontal theta increases, and the central and parietal delta decreases, which indicates a better intense of attention was put into the problem-solving task. However, the relative band power of frontal and parietal alpha exhibited a little increase as the task complexity escalated, indicating a potential decline in attention levels during the problem-solving activity. Besides, the ratio between theta and beta was also not presented as the ideal model. This result may be caused by lost calibration or bad connections between some channels of EEG collecting headset and subject's scalp. Drawing precise reasons on this issue is challenging due to the insufficient number of trials and subjects involved.

Nevertheless, by analyzing the cognitive load condition and the attention degree while the subjects were facing the problem-solving task, the researchers could infer that some mistakes made by the subject were not because of the inefficiency of the training program but due to loss of attention or the lack of ability to keep on a high cognitive load level for a long time. In this example, the subject stayed focused during the whole session and solved all three violations (presented in Fig.6) successfully. However, the presented example contains a short number of decisions with only simple construction scenes and a limited number of violations. It's relatively easy to keep focused on the problem-solving task. For subjects who face a more complex scene and can't solve all violations, the reason for the mistakes (i.e., performance on correct inferences to solve the problem) will become part of the analysis, including the effectiveness of the MX intervention for the training program.

5. CONCLUSION AND FUTURE WORK

The presented research is a successful design and development of a method for the effectiveness of assessment safety training. The approach includes in its development the design and construction documents of the construction project site to build a virtual construction site. The information was used to build an MX environment for the learner's self-exploration using a navigation system, enabling the learner to mimic the real workplace with the advantage of a mixed-reality device. The method uses EEG signals to estimate cognitive conditions that inform the users' effort in decision-making while solving a problem relating to OSHA violation (i.e., virtual safety inspections in the MX environment). The technology consists of an MX device and a 16-channel EEG headset. Subjects could walk freely in the experimental space, as the portable EEG and mixed-reality devices allow them to collect the data wirelessly to a local network set for the experimentation. With the model developed, the researchers could successfully and accurately assess the subject's cognitive load and attention levels while solving the construction safety-check problem. The outcome provides new and comprehensive information that helps to analyze the performance during learning and problem-solving. With the developed method, the researchers could overcome the bias from self-report evaluation or any paper-based test and get a comprehensive and personalized performance analysis. For future work, the researchers will model the effects of the cognitive load and attention degree analysis by applying machine learning algorithms for inference on the subjects' behavior during problem-solving tasks.

6. ACKNOWLEDGMENT

This material is based upon work supported by the National Science Foundation under Grants No. (2044444), 2222870, and (2040422). Any opinions, findings, conclusions, or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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EVALUATION OF COMPUTER VISION-AIDED MULTIMEDIA LEARNING IN CONSTRUCTION ENGINEERING EDUCATION

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ABSTRACT: *Due to the practice-oriented nature of construction engineering education and barriers associated with physical site visits, videos are invaluable means to expose students to practical curricula content. Prior studies have investigated various design principles of multimedia pedagogical tools to enhance student learning and reduce cognitive load. These design principles and computer vision techniques can afford the design and usage of a multimedia learning environment with annotated content to teach students construction safety practices. Hence, using subjective and objective measures such as self-reported cognitive load, eye tracking metrics and verbal feedback, this study assesses the effectiveness of a computer vision-aided multimedia learning environment as well as examines variations across students' demographics. Students were exposed to both annotated and unannotated versions of the learning environment. The annotated version of the learning environment was considered more effective in triggering students' attention to learning content, but higher cognitive load levels were reported by participants. The same demographic groups that dwelled longer and on more annotated areas of interest also reported higher overall cognitive load. Keeping with individual differences principle of multimedia learning, demographic variations in participants' cognitive load and effectiveness of the learning environment were reported. The study provides implications for instructors in construction engineering programs on effective use of computer vision-aided annotated videos as instructional materials. This study could serve as a benchmark for future studies on artificial intelligence techniques for signaling in multimedia learning. This study reveals the affordances of computer vision-aided multimedia learning in construction engineering education and the need for adaptation of multimedia learning tools to students' demographics.*

KEYWORDS*: Computer vision, construction engineering education, demographic differences, multimedia learning, video.*

1. INTRODUCTION

Construction-related disciplines are applied science; hence they are rich in practical components which are usually difficult for instructors to cover in the classroom (Gunhan, 2015). The imbalance between theory and practice has been one of the challenges in preparing students for the workplace (Afonso et al., 2012). Hence, academia is in constant effort to achieve a proper blend of theory and practice (Bozoglu, 2016). Site visits are being used to circumvent this challenge by exposing students to real-world examples, spatio-temporal scenarios of construction operations and interaction with practitioners (Eiris Pereira & Gheisari, 2019). However, barriers associated with site visits such as safety, coordination, distance/location, limited what-if scenarios, and concerns for disabled students(Eiris Pereira & Gheisari, 2019) have necessitated the need for new methods of bringing practical examples into the classroom. Videos are now increasingly being widely used as pedagogical tools to address these limitations (Shojaei et al., 2021). Videos enable instructors to bring the real world into the classroom. Videos also allow for experiments, site visits, and demonstrations that otherwise would have been impossible. Beyond knowledge transmission, videos expose students to diverse experiences, attitudes, and emotions and promote interactions and discussions (Ferreira et al., 2013). However, the use of videos also comes with some challenges. For example, if not intelligently designed, videos could be ineffective for learning because they could increase cognitive load, and not capture learners' attention (De Koning et al., 2009). In addition, videos could contain non-essential information which could be distracting to learners. These downsides of videos have been earlier reported (Homer et al., 2008). To circumvent these challenges, the adoption of multimedia learning principles such as removal of extraneous content and signaling of important learning content are effective measures (Mayer & Fiorella, 2014). Signaling involves the use of cues (e.g., arrow, boundary boxes, color contrast) to point out important learning content to learners in a multimedia environment. In other domains, previous studies have demonstrated the effectiveness of these techniques in ensuring that videos are effective pedagogical tools (De Koning et al., 2009; Navarro et al., 2015).

Given the advances in computing, its affordances and wide applications, manual signaling methods which could be laborious, undynamic and time intensive can be replaced with automation afforded by artificial intelligence. By leveraging computer vision (CV) techniques (such as object and interaction detection), construction videos can be automatically annotated to call out specific learning contents. This has been demonstrated in other endeavors such as detecting human daily activities using convolutional neural networks (Zhang et al., 2017). Adopting this in construction engineering education is important given the need to visualize theoretical concepts,

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Anthony Yusuf, Adedeji Afolabi, Abiola Akanmu, Johnson Olayiwola, *Evaluation of Computer Vision-Aided Multimedia Learning in Construction Engineering Education,* pp. 242-253, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.23

understand the pace and sequence of construction tasks, and spatiotemporal nature of construction activities (Eiris Pereira & Gheisari, 2019). Previous studies (Abdulrahaman et al., 2020; Stark et al., 2018) have highlighted the need to evaluate the efficacy of multimedia learning environments. To evaluate multimedia pedagogical tools, learners' cognitive load level and demographic differences have been suggested as primary considerations (Grimley, 2007). Also, earlier studies have combined objective and subjective measures and compared two or more multimedia learning environments (Abdulrahaman et al., 2020; Stark et al., 2018). Despite the potential of multimedia learning in construction engineering education, it has received little attention in literature, especially the application of CV in multimedia learning. Hence, this study compared two multimedia learning environments from the lens of demographic differences to evaluate the effectiveness of CV-aided multimedia learning in construction engineering education.

2. BACKGROUND

2.1 Application of Computer Vision in Education

Computer vision is being increasingly leveraged in several educational contexts because of its value to conventional educational methods by improving teaching and learning (Savov et al., 2018; Sophokleous et al., 2021). For instance, using a face recognition algorithm, Savov et al. (2018) combined computer vision, and internet of things to provide engaging experience for students. The study demonstrated the efficacy of computer vision through adaptation to learners' facial expression to help instructors tailor the teaching process to learners' preferences. Tetiana et al. (2021) also leveraged computer vision and augmented reality to allow students to interact with and obtain additional virtual information about research objects. This helped to promote effective interaction between students and educational material. Similarly, using facial emotions, pose estimation, and head rotation, Poonja et al. (2023) developed a computer vision-based system to detect students' engagement in online learning. Computer vision has been adopted in other educational context such as enhancing the teaching of mechatronics (Tudić et al., 2022), in distance education of new generation labor productivity (Zhao & Li, 2021), as well as educational robotics in K-12 education (Sophokleous et al., 2021). Interaction and object detection techniques of computer vision can be leveraged to signal essential learning contents in videos for teaching purposes. For example, Tang et al. (2020) used Faster Region-proposal Convolutional Neural Network (Faster RCNN) to detect workers and materials for safety monitoring. Using deep residual learning network, Hashimoto et al. (2019) used computer vision for automated operative step detection during Laparoscopic Sleeve Gastrectomy. Similarly, Aronson (2018) demonstrated the efficacy of computer vision for signaling violation of human right in videos. However, there are scarce studies that demonstrated the effectiveness of computer vision for signaling in multimedia learning.

2.2 Evaluation of Multimedia Learning Tools

To evaluate multimedia learning tools, a comparison approach which involves comparing two or more multimedia pedagogical tools is a common method (Abdulrahaman et al., 2020). For example, Chiu et al. (2018) compared the efficacy of annotated and unannotated versions of a video to teach cardiopulmonary resuscitation. Using pre and posttests, eye tracking metrics, satisfaction and self-reported cognitive load questionnaires, the study reported that students that learned with annotations had lower cognitive load, concentrated more on the critical parts of the instructional video, and thus learned more effectively and easily. Also, combinations of objective and subjective measures have been encouraged in usability evaluation (Abdulrahaman et al., 2020). This is due to the limitations of subjective measures such as risk of prejudice, lack of response, and lack of supporting evidence for respondents' ratings (Kelley et al., 2003). Objective measures such as eye tracking metrics (e.g., fixations and dwell times) are widely used in the usability evaluation of multimedia learning tools (Molina et al., 2018; Stark et al., 2018). National Aeronautics and Space Administration Task Load Index (NASA-TLX) is a widely used subjective evaluation tool for assessing cognitive workload. NASA TLX assessed cognitive workload across six subscales: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration (Sharek, 2011). Eye Tracking and NASA TLX have been used in previous studies (Latifzadeh et al., 2020; Law et al., 2010) for the evaluation of multimedia pedagogical tools. Other subjective measures such as think-aloud protocol, interview, and verbal feedback are also being used (Abdulrahaman et al., 2020). Also, to evaluate the usability of multimedia pedagogical tools, demographic differences such as gender (Grimley, 2007), academic level, academic program (Castro-Alonso et al., 2019), ethnicity (Moreno & Flowerday, 2006) and prior experience (Kalyuga et al., 2000) are deemed important considerations.

3. METHODOLOGY

3.1 Overview

The study evaluated the efficacy of an annotated video designed to teach construction students different construction safety practices. A comparison approach was adopted. Students were exposed to two learning environments. One was designed with computer-vision aided signals or cues to call out essential learning content while the other was not. Subjective and objective measures of the participants in the two learning environments were compared. In addition, keeping with individual differences principle of multimedia learning, demographic variations in participants' cognitive load and eye tracking metrics in the annotated learning environment were assessed.

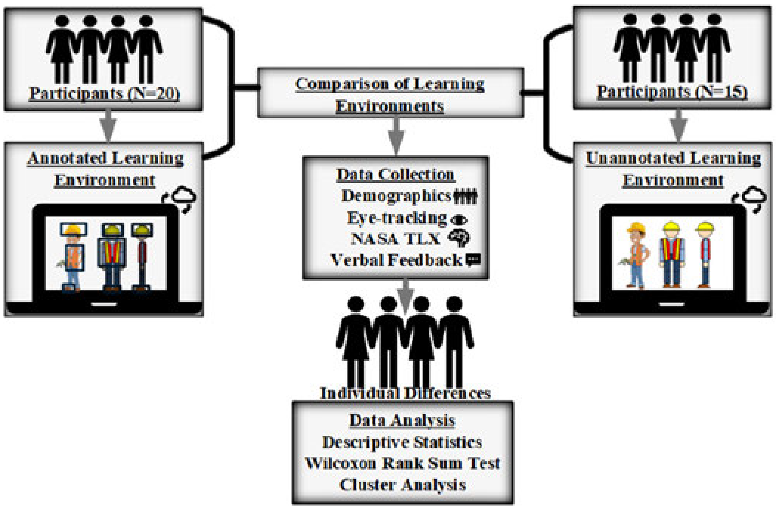

Fig. 1: Overview of Methodology

3.2 The Learning Environments: Annotated and Unannotated Videos

The two versions of the video had the same contents, each about 6-minutes long. The videos contain both visual and audio presentations of eleven (11) construction safety practices. These include Personal Protective Equipment (PPE), Situational awareness (SA), Secure workers at height (SWH), Securing materials (SM), Exclusion zone (EZ), Deep excavation (DE), Signage (S), Fall protection (FP), Mobile phone use (MPU), Ladder use (LU), Ergonomics (ER). These safety practices were identified by Olayiwola, Yusuf, et al. (2023) as critical to complement classroom teaching during site visits. The safety practices represent areas of interest (AOIs). Safety practices were chosen because Pedro et al. (2016) highlighted the need for knowledge of safety practices in preparing the future workforce. The annotated video contains computer vision-aided signals to call-out the safety practices while the unannotated video does not. Both object and interaction detection techniques of computer vision were used in this study. Faster RCNN, a deep learning technique was combined with Visual Geometry Group network (VGG16) (a convolution neural network architecture) to signal the construction safety practices with boundary boxes. Visual translation embedding network (VTransE) was used as the interaction detection technique. The details of the design and development of the annotated learning environment are presented in Olayiwola, Akanmu, et al. (2023). Examples of frames from the annotated and unannotated videos are shown in Figure 2.

3.3 Participants and study approval

After the Virginia Tech Institutional Review Board approved the study, thirty-five (35) participants who are students in construction-related programs volunteered to participate. Twenty (20) of them used the annotated learning environment while fifteen (15) used the unannotated learning environment. All the participants are between 20 to 24 years old. The participants' demographics are shown in Table 1 below.

(a) Sample frame of annotated video

(b) Sample frame of unannotated video

Fig. 2: Frames of Annotated and Unannotated Videos.

Table 1: Participants' Demographic Information.

Demographics	Experimental Group (N=20)	Control Group (N=15)
Gender		
Male	12	12
Female	8	3
Academic Program		
Building Construction (BC)	5	5
Construction Engineering and Management (CEM)	9	10
Civil and Environmental Engineering (CEE)	6	-
Academic Level		
Junior	4	10
Sophomore	16	5
Years of construction experience		
Less than 2	13	11
2-5	7	4
Ethnicity		
White/Caucasian	12	9
Asian	5	3
African American	2	2
Hispanic/Latino	1	1

3.4 Experimental design and Data collection

Before the experiments commenced, every participant was intimated with the workflow of the experimental procedure. Thereafter, the participants signed the informed consent form and completed the demographic questionnaire. A web-based eye tracker (Gaze-recorder) was used in this study. The participants' eyes were calibrated, and then they watched the 6-minute video of construction safety practices. Eye-tracking data was collected as the participants watched the video. Two separate experiments were conducted. In the first experiment, the experimental group (n = 20) was exposed to the annotated video while in the second experiment, the control group (n = 15) was exposed to the unannotated video. After every session, participants completed three subscales of the NASA-TLX questionnaire (i.e., Mental demand, Effort, and Frustration). These subscales have been used to assess cognitive load in multimedia learning (Refat et al., 2020). Finally, the participants' verbal feedback was audio-recorded. Each session lasted for about one (1) hour.

3.5 Data analysis

Dwell times of the participants were collected for the eleven AOIs in the videos. Wilcoxon Rank Sum Test was used to test for statistically significant differences since the comparisons were between two independent groups and independent observations. Descriptive statistics were used for the self-reported cognitive load. MS Office Excel and SPSS were used for the analysis. The verbal feedback was transcribed and analyzed using cluster analysis. The analyses were done by comparing the participants' dwell times on the AOIs of the annotated and unannotated videos and the demographic differences of the participants.

4. RESULTS AND DISCUSSION

4.1 Dwell Time Comparison in Annotated and Unannotated Video

As shown in Figure 3, significant differences in the dwell times were found between the annotated and unannotated videos for seven (7) AOIs of which four (4) had significantly higher dwell times in the annotated video. These include PPE, Situational Awareness, Securing Material, and Signage ($p < 0.05$). The overall dwell time of the participants was higher in the unannotated environment although no statistically significant difference was observed. However, the participants dwelled longer on more of the AOIs in the annotated video. The participants dwelled longer on 7 out of the 11 safety practices in the annotated video. In the unannotated video, the participants only dwelled longer on four (4) safety practices, which include Secure workers at height, Fall Protection, Use of Mobile Phone and Ergonomics. This result shows that although the participants spent more time in the unannotated environment, they did not dwell longer on more AOIs. Whereas the participants spent less time in the annotated environment but dwell longer on the AOIs. This shows that the annotation was effective to direct the learners to important learning content and to stimulate their interest. This finding agrees with Molina et al. (2018) who explained that learners might dwell more on AOIs in multimedia learning. The higher dwell times on the AOIs in the annotated video shows the extent of focus and interest in the AOIs (Bojko, 2013; Carter & Luke, 2020). This result aligns with the findings of previous studies (Molina et al., 2018; Navarro et al., 2015) which underscored the potential of signals to trigger learners' interest, improved learners' visual search efficiency and provide greater visibility for important learning content.

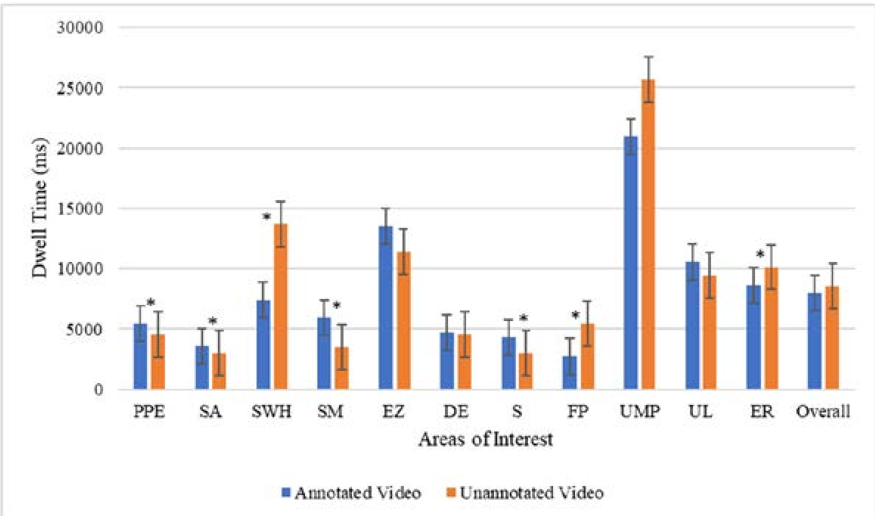

Fig. 3: Dwell Time on AOI

4.2 Comparison of Demographic Differences within Annotated Video

4.2.1 Gender

Within the annotated environment, gender differences were observed, as shown in Figure 4. On the overall, female students dwelled longer on the AOIs than their male counterparts. The overall dwell time of the female students was statistically higher ($p < 0.05$). Also, the female participants dwelled more on each of the AOIs than their male counterparts. This phenomenon reveals that signals were efficacious in drawing the attention and stimulating the interest of female students than male students. The female participants' dwell times on the AOIs were significantly higher for three (3) AOIs, which include Secure Workers at Height, Deep Excavation and Use of Mobile Phone. This could mean that female students prefer to learn with annotated videos than male students. This could be helpful to instructors in their choice of instructional materials. This finding contributes to prior studies (Grimley, 2007; Saha & Halder, 2016) which have shown gender differences in information process in multimedia learning. The finding agrees with Dousay and Trujillo (2019) who reported that females had higher situational interest in multimedia learning than males.

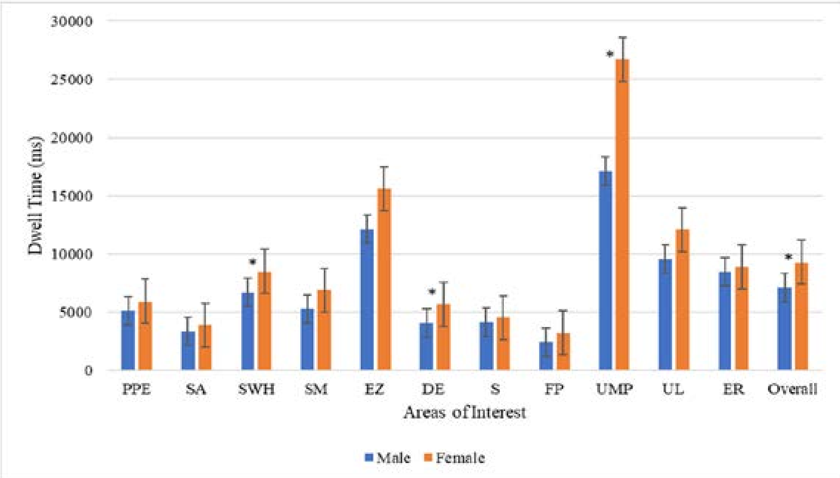

Fig. 4: Male and Female Dwell Time for Annotated Video

4.2.2 Academic Level

On the overall, Figure 5 shows that the senior-level students dwelled longer (although not significant, $p>0.05$) on the annotated video than junior-level students. Also, the senior-level students dwelled more on nine (9) out of the eleven (11) AOIs than their Junior-level counterparts. The Senior-level participants dwelled more on all AOIs except Use of Mobile Phone and Ergonomics. The results showed that the Senior-level participants significantly dwelled longer ($p<0.05$) on Exclusion Zone ($p<0.05$). The academic level of the students could be synonymous with prior knowledge. Although, previous studies (Grimley, 2007; Kalyuga, 2013) have noted that multimedia learning would be effective for learners with lower prior knowledge, the findings of this study differ from Navarro et al. (2015) who reported that students of lower academic levels dwelled more on AOIs while senior students only take a glance. The difference in the finding could be because the participants in this study were college students (aged 20-24 years) while those in prior studies (Grimley, 2007; Navarro et al., 2015) were primary school pupils (aged $\leq$ 11 years). Also, in this study, better than junior-level participants, the senior-level participants might have been more willing to explore the annotated learning environment and found the signaled concepts more engaging which might have been responsible for dwelling on more signaled concepts. This result contributes to earlier studies, e.g., Castro-Alonso et al. (2019), on academic level-based differences in multimedia learning.

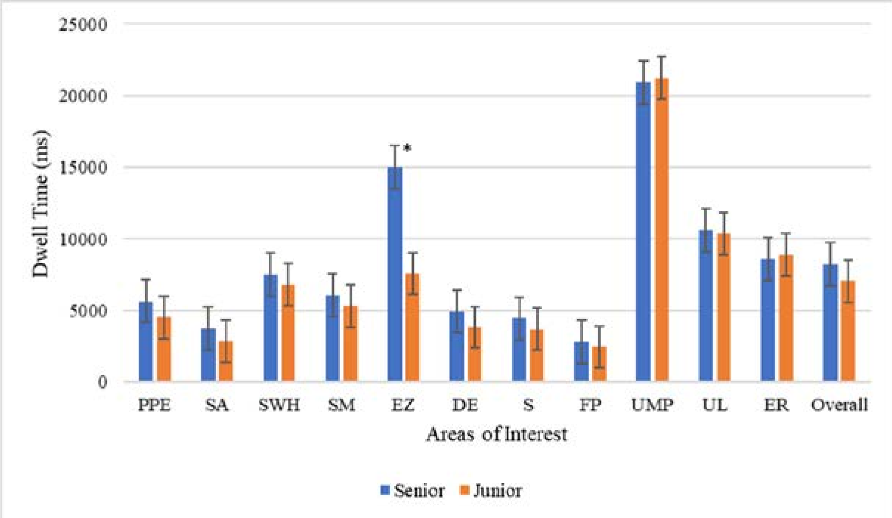

Fig. 5: Junior and Senior Dwell Time for Annotated Video

4.2.3 Years of Experience

As shown in Figure 6, although no statistically significant difference was observed, overall, students with 0-2 years of experience had higher dwell time on the AOIs. The students dwelled more on the AOIs (8 out of 11) than those with 2-5 years of experience. The students with 2-5 years of experience only dwelled longer on PPE, Situational Awareness and Secure of Materials. This result shows that the learners with lower experience would perceive better learning benefits with the annotated learning environment. This study contributes to prior studies e.g., Kalyuga et al. (2000) that have demonstrated differences based on prior experience in multimedia learning.

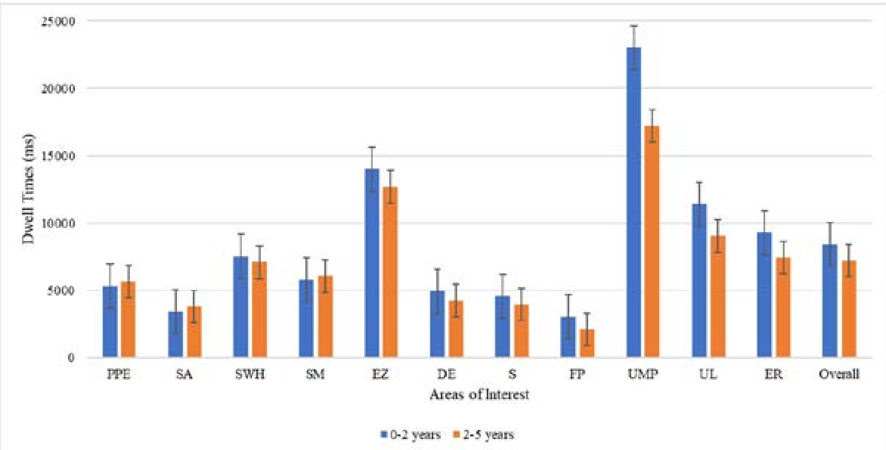

Fig. 6: Dwell Time for Annotated Video Based on Years of Experience

4.2.4 Academic Program

No statistically significant difference was observed in the comparison based on students' academic program. On the overall, students in CEE dwelled longer on more AOIs than those in BC and CEM respectively (Figure 7). For six (6) of the AOIs namely, Situational Awareness, Exclusion Zone, Deep Excavation, Fall Protection, Use of Mobile Phone, Use of Ladder, the ascending order of the increase in dwell time on the AOIs is BC students, CEM students and CEE students. The variation observed based on academic programs could be due to differences in the emphasis of each program even though they are all aspects of construction education. For instance, Abudayyeh et al. (2000) pointed out that the CEE program is focused more on design of facilities; CEM program has concentration on achieving a balance between the engineering and management component of construction, while BC program has emphasis on management and business components of construction. Hence, the differences in the educational background of the students could have been responsible for the variations. For example, since CEE students are in a program that focused on design of infrastructural facilities, they might have been less familiar with the construction safety practices in the annotated video compared to their counterparts in CEM and BC programs. This could account for their higher dwell times on most of the AOIs. This result contributes to earlier studies e.g., Castro-Alonso et al. (2019) on differences based on academic program in multimedia learning.

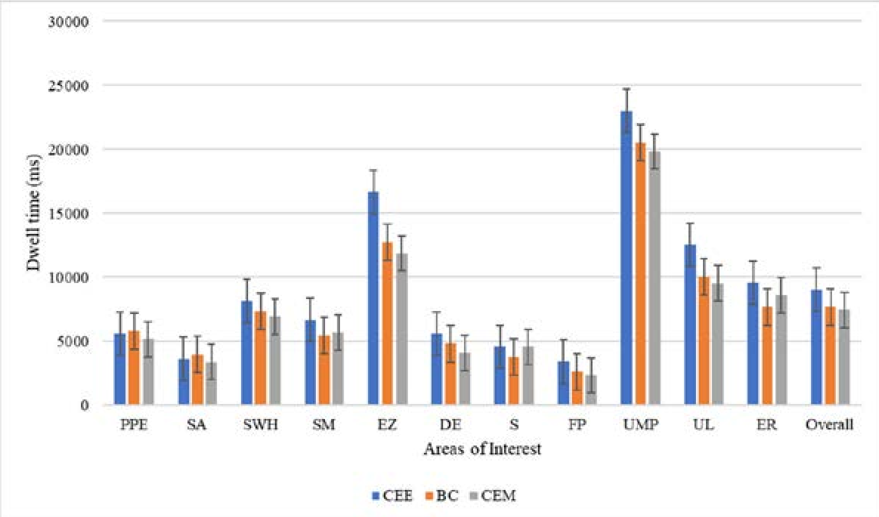

Fig. 7: Dwell Time for Annotated Video Based on Academic Program

4.2.5 Ethnicity

Though without any significant difference, the result reveals that on the overall, White students dwelled longer on the annotated video (Figure 8). They also dwelled longer on more AOIs (6 out of 11) than students of other ethnicities. Studies comparing ethnic differences in multimedia learning are scarce. In this study, due to the small sample sizes, only White students who made up 60% of the participants were compared with other ethnicities. This study contributes to the few existing studies such as Moreno and Flowerday (2006) that have examined ethnic differences in multimedia learning.

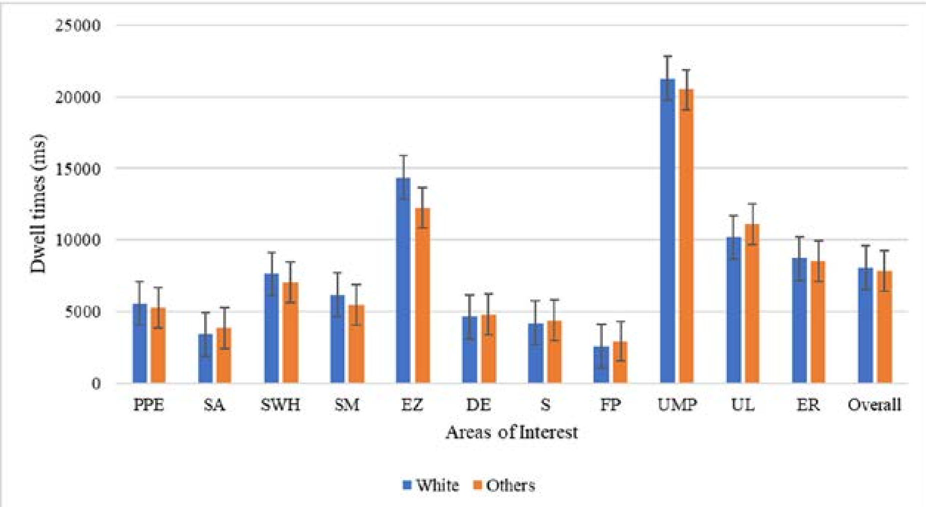

Fig. 8: Dwell Time for Annotated Video Based on Ethnicity

4.3 Cognitive Load

As shown in Figure 9, the participants reported higher effort and frustration for the annotated video, however, they reported lower mental demand for the same. This shows that it was not mentally demanding to learn with the annotated video, but participants put in more effort and experienced higher frustration. This could be because of their unfamiliarity with the annotated video, the effect could be abated as learners get used to the video. Overall, the participants experienced a higher cognitive load in the annotated learning environment. No significant difference was observed between the annotated and unannotated video ($p > 0.05$). This result differs from Chiu et al. (2018) who reported that students who learned with annotated video experienced lower cognitive load. This difference could be attributed to other factors such as participants' ethnicity (Moreno & Flowerday, 2006), visual preference (Homer et al., 2008) and media type (Castro-Alonso et al., 2019) which are moderating variables in multimedia learning. For instance, Homer et al. (2008) reported that low visual-preference learners experienced higher cognitive load than high visual-preference learners in learning with video.

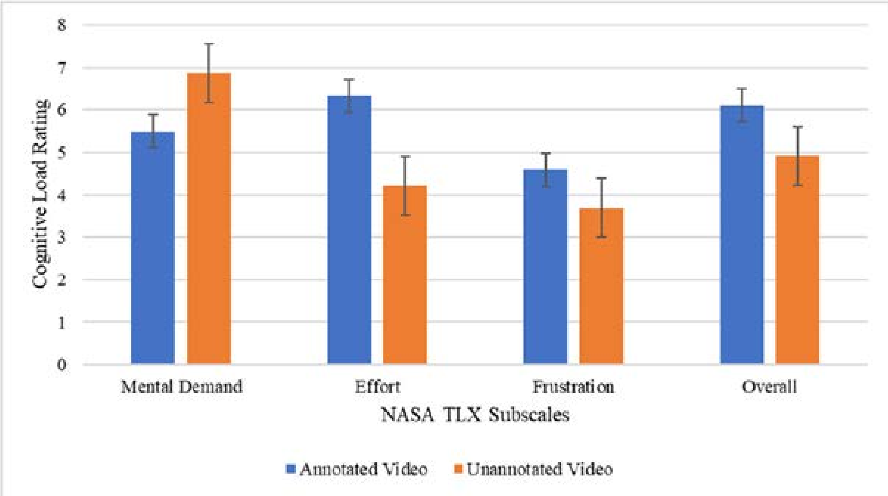

Fig. 9: Participants' ratings of perceived mental demand, effort, and frustration after interaction with both video

The demographic comparison of cognitive load in annotated video is shown in Figure 10. Although no statistically significant difference in any of the comparisons (p>0.05), female participants reported higher cognitive load compared to male participants. Similarly, participants with 0-2 years of experience self-reported higher cognitive load than their colleagues with 2-5 years of experience. For the academic programs, CEE students reported the highest cognitive load, followed by CEM students, while BC students had the lowest cognitive load rating. Demographic comparison reveals variations in the cognitive load level of the students. This variation could help instructors to design and adapt multimedia learning environments to suit learners of various categories. This is especially important to instructors especially those in engineering-construction educational programs, where effort is required to attract and retain female high school students and those from underrepresented groups (Choi et al., 2022).

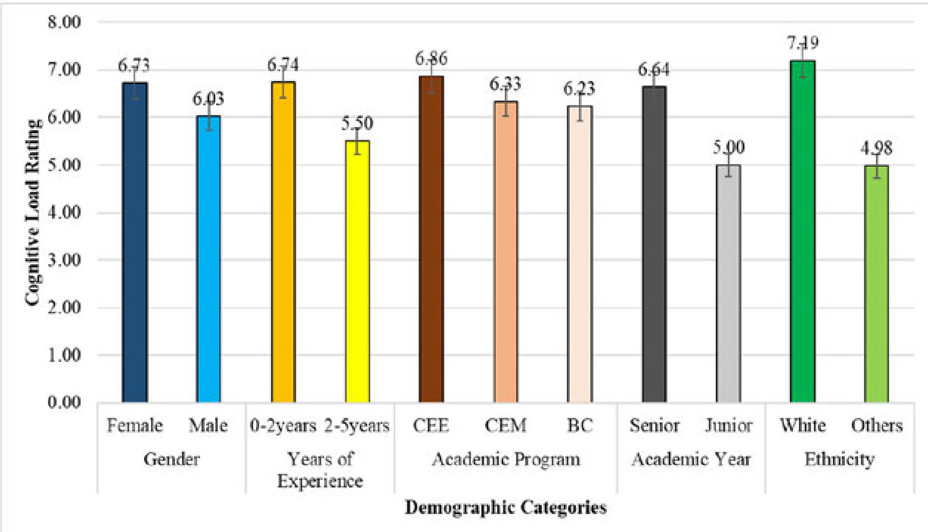

Fig. 10: Demographic comparison of cognitive load in annotated video

4.4 Verbal Feedback

Most of the participants that watched the annotated video opined that the annotation was effective in making them learn easier. The participants reported that the annotation helped them to focus on learning content and their attention was held. This is because in addition to the audio narration, the annotation helped the student to easily identify specific areas to focus on in the video which helped them to better understand the learning contents. Only three participants reported that the signals were distracting. The participants suggested using arrows instead of boundary boxes and highlighting their content because some learners might focus on the boundary boxes more than the contents within them. Some participants also suggested making the video more interactive and reducing the tempo. The students attested to the potential of the video for online courses and helping to learn about more construction practices without having to visit a job site.

5. CONCLUSION, LIMITATIONS AND FUTURE WORK

Characteristics of learners influence cognitive load and the efficacy of designs in multimedia learning. Hence, it is important to evaluate multimedia pedagogical tools to assess their suitability for intended context, purpose, and users. This study evaluates the efficacy of an annotated video which is a computer-vision-aided multimedia learning for teaching construction safety practices. The study reveals that computer vision generated signals were effective in drawing the intention of learners to fixate on AOIs. Within the annotated learning environment, female students, students with 0-2 years of experience, senior-level students, CEE students, and white students dwell longer and on more AOIs than their counterparts. However, these categories of participants reported higher overall cognitive load for the annotated video compared to their counterparts. The study also shows demographic differences in the cognitive load level of participants based on gender, ethnicity, academic level, years of experience and academic program. The results reveal that the demographic classes that dwelled more on the AOIs also reported a higher cognitive load. The results of this study could help instructors in engineering-construction education programs to effectively use annotated videos as instructional materials. This study could serve as a benchmark for future studies on artificial intelligence techniques for signaling in multimedia learning. The study opened a discussion on demographic differences in multimedia learning within the construction engineering education domain as well as the efficacy of artificial intelligence techniques in the design of multimedia pedagogical tools. This study has some limitations which could be the focus of future research. For example, only subjective rating of cognitive load was used, future research could combine both objective and subjective measures to assess cognitive load level in multimedia learning. Also, the small sample size of this study could have been responsible for some lack of significant differences in the comparisons made across the demographics of the participants. The small sample size also limits the generalizability of the findings. Future research could use higher sample sizes. Also, effects of age differences and academic levels (i.e., elementary school, high school, and college) of participants in multimedia learning could be the subject of future work.

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BIM-BASED OPEN LEARNING RESOURCES REPOSITORY FOR THE BENEDICT PROJECT

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ABSTRACT: *In the field of AEC, Architecture Engineering and Construction, Building Information Modelling has increasingly assumed an important role, especially for construction simulation. BIM is needed for various building and management systems, particularly for project construction management. Students, teachers and operators of AEC need to have the availability of data, reports, pieces of information that allows to create BIM. "BENEDICT" is an European Erasmus project that has the aim of developing a web-based platform for BIM teaching that has a tight relationship with the AEC industry. Therefore, a BIM-enabled Learning Environment (BLE) can be used to implement BIM-based project planning and control system for learners and future practitioners, with Open Learning Resources. Open Learning Resources (OLR) are learning, teaching and research materials in any format and medium that are useful for teaching, learning, and assessing and for research purposes. In addition to the BLE platform, a BIM-model repository was developed to store information for each component of the project and of the learning activities. The repository can also store OLR and students' outputs. The BLE repository has the task of helping students and practitioners to implement BIM actual project models by developing an on-line repository of digital models, objects and elements, therefore providing knowledge transfer between different players.*

KEYWORDS: *Building Information Modelling, Benedict project, Open Learning Resources, Construction.*

1. INTRODUCTION

The construction industry is one of the largest in the world economy, with about $ 10 trillion spent every year for construction related goods and services. However, the industry productivity has lagged behind that of other industrial sectors, such as manufacturing and retail, that have implemented digitization and innovation, increasing their productivity over time. This productivity gap has many causes, and Building Information Modelling (BIM) is considered one fundamental strategy to recover the desired level of performance (European Construction Sector Observatory, 2021). Building Information Modelling (BIM) is the use of a shared digital representation of a built object to facilitate design, construction and operation processes to form a reliable basis for decisions (ISO 294811:2016). A built object can be a building, a road, a bridge, a process plant, everything that belongs to the built environment. A building construction information model is a shared digital representation of physical and functional characteristics of a built object (ISO TS 12911), therefore the term modelling addresses the process of managing information related to the facilities and project in order to coordinate multiple inputs and outputs, regardless of the specific implementation. Therefore, BIM is a method or strategy, not a tool. In the construction sector, knowledge transfer between different players, owner, designers, construction specialists, and project operators, together with project procurement take place by data exchange, i.e. information exchange. Among the specific features of the BIM methodology there is the ability to store information for each individual component of the project, including three dimensional properties and data concerning materials, building products, structure, quality performances, construction operations, transformation or installation stages, maintenance, time and cost data, sustainability and health and safety related information. Therefore, the fundamental element of this method is a digital model capable of n-dimensional representation of a building. BIM is considered a powerful approach to improve productivity in Architecture, Engineering and Construction sector. The use of BIM is spreading rapidly in many countries, covering a wide range of project both in the public and private sectors. Digitization of construction sector involves the need of helping students and practitioners to implement BIM actual project models by developing an on-line repository of digital models, objects and elements. Particularly focusing on educational processes, there is a strong need of developing a shared, online BIM models repository to provide an effective and coherent basis for BIM project implementation (Becerik-Gerber, 2012, Boeykens et al. , 2013, Clevenger et al. 2013, Puolitaival, Forsythe, 2016) The BENEDICT project, BIM-Enabled Learning Environment for Digital

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Marco Bragadin, Caterina Morganti, Pier Carlo Ricci, Emlyn Witt, Kalle Kähkönen, Puolitaival Taija, *BIM-Based Open Learning Resources Repository for the Benedict Project,* pp. 254-265, DOI 10.36253/979-12-215-0289-3.24

Construction, is an Erasmus+ strategic partnership between the Department of Civil Engineering and Architecture at Tallinn University of Technology (Estonia), the Civil Engineering Unit of Tampere University (Finland) and the Department of Architecture at the University of Bologna (Italy). The BENEDICT project deals with how to teach courses at university level with BIM tools, in particular through the use of an IT platform for BIM models (Olowa et al. 2022, Ruutman et al., 2022, Witt, Kahkonen, 2019). The fundamental needs of Real Estate and Construction professionals and students, Architects, Engineers, Construction Managers, concerning Building Information Modelling involve the design, development and implementation of various building and management systems, for instance:

- Architectural systems and space coordination: i.e architectural layout and spatial units (size and coordination, proximity relationships, internal partitions),
- Structural systems: i.e foundations, poles, structural slabs and basement structures, superstructure, reinforced concrete framework, GLT and solid timber frame, CLT and prefabricated panels, floors and roof structures;
- Enclosure systems: i.e. architectural language and facades, doors and windows, architectural finishes, waterproofing, roofing;
- Mechanical /Electrical / Plumbing - MEP systems: i.e. connection systems i.e. elevators, mobile staircases,
- Construction project systems: i.e construction site provisions and equipment (e.g. scaffoldings, tower crane, formworks etc.).
- Project Construction Management systems: i.e project control methods and tools concerning project description, integration and implementation, project planning and time management, project risk management, project cost, quality and resources management.

The needs of BLE users – learners, teachers, system administrators – consist in having the availability of data, reports, pieces of information concerning architecture – engineering systems. The technical data and information concerning design, development and installation of the building and its project management allows BLE users to create the Building Information Model. For example, construction management students will need a set of case studies to be tested with practical exercises and the Open Learning Resources will be supplied as actual case studies - each case study consisting of a building or facility that has been designed and engineered in industry or in previous courses. Learning experiences using these will greatly enhance BIM-enabled learning where BIM-based workflows will provide immersive learning and training opportunities. BIM – enabled learning can use a virtual platform, a web site and repository, where all BIM models, examples and data can be stored and used. This creates a BIM enabled Learning Environment, BLE. The BLE provides the learning environment or web platform specifically designed to support this type of learning. Key resources for the use of the BLE are Open Learning Resources.

2. OPEN LEARNING RESOURCES AND VIRTUAL DATA ENVIRONMENTS

The simulation of actual design and project management activities that takes place in teaching AEC modules with BIM as a media has the need of a common data environment. A Common Data Environment CDE is a single source of information for any given project, used to collect, manage, and disseminate all relevant approved project documents for multidisciplinary teams in a managed process (BS EN ISO 19650). A CDE has four different environments where models and data can be stored: the work in progress area, the shared area, the published area and the archive. With the aim of creating a virtual environment for learning and teaching activities two different virtual environment were developed, the BLE platform and the OLR repository. The OLR repository is not a CDE because does not fulfill the requirements of ISO 19650, but was developed with the aim of storing BIM models and data. The BLE platform and repository create a virtual environment where teachers, learners and system administrators can store data, reports, pieces of information concerning architecture and engineering systems of the built object under design. All of these technical data and information concerning the different stages of production of a building, design, i.e. concept design, space coordination and technical design, construction and installation, operation and maintenance allows user to create the Building Information Model. Construction Management students, as an example, will need to use a set of case studies to be tested with practical exercises.

Open Learning Resources (OLR) or Open Educational Resources (OER) will be supplied as actual case studies – each case consisting of a building or a facility that has been designed and engineered in industry or in previous courses. The BLE, will be used to store and manage both OLR and BIM models, output of the students' work. Therefore, the BIM – Enabled learning environment will provide a virtual environment where educational activities in the AEC sector can be performed using BIM-based technology. Open Educational Resources (OER) are learning, teaching and research materials in any format and medium that reside in the public domain or are under copyright that have been released under an open license, that permit no-cost access, re-use, re-purpose, adaptation and redistribution by others (UNESCO, 2019). Open educational resources (OER) are freely accessible, openly licensed instructional materials such as text, media, and other digital assets that are useful for teaching, learning, and assessing, as well as for research purposes. The term "OER" describes publicly accessible materials and resources for any user to use, re-mix, improve, and redistribute under some licenses. These are designed to reduce accessibility barriers by implementing best practices in teaching and to be adapted for local unique contexts. The BENEDICT project has the aim of promoting a new concept of learning/training in the REC sector. The Open Learning Resources are essential for users to benefit from the BLE as they provide real (or near-real) project data for learners to work with and this will demonstrate the practical implementation of BIM workflows. The BIM-enabled learning environment creates a repository of OLR that can be descriptions of projects, technical BIM models, and project plans (table 1).

Table 1: Type of Open Learning Resources.

OLR	Examples	File format
Descriptions of projects	project objectives; site description and analysis; media concerning the site; building overall concept description; statement of work (SOW); building systems reports, drawings and calculation	.docx; .xlsx; .pdf; .dwg; dxf; xml; mp4; JPG; (…)
Technical BIM models	BIM objects; BIM model	.ifc
Project Plans	architecture and envelope layout; structure layout; MEP systems layout, construction process. bills of quantities; budgets; schedules; resource estimation, procurement documentation concerning materials, products, components and other supplies; safety plans	docx; .xlsx; .pdf; .dwg; dxf; xml; mp4; JPG; (…)

Open learning resources for BLE need to be checked before model processing. BIM models should be checked also concerning the achievement of the desired level of detail / level of development (LOD) and quality assessment consisting in code checking and model checking. The purpose of defining the level of information need is to prevent delivery of too much or too little information (ISO 19650-1:2018). In particular, the project information requirements (PIR), in relation to the delivery of an asset indicate for what, when, how and for whom information is to be produced. The Level of Information Need (LOIN) has to be set by applying the BS EN 17412-1 that indicates the framework to set the LOIN. Firstly, four pre-requirements addressing the context needed to identify the information content have to be set: BIM uses, milestone, actors, object. After this stage, the level of information need must be set concerning geometrical information, alphanumerical information, and documentation (BS EN17412-1:2020) (figure 1, figure 2). In the specific case of construction management – oriented applications, Open Learning Resources will be supplied to students and applicants as actual case studies. Each case study consists in one or more than one building or civil engineering facility that has been designed and engineered in previous courses of the university programme, or provided by teachers or by the BENEDICT project associated partners. As an example, the following documentation / information can be produced by the students of construction engineering and management courses with Building Information Modeling.

- Project Planning, job site design & safety planning;
- Work Breakdown Structure;

- Construction project schedule;
- Construction site design;
- 4D BIM animation.

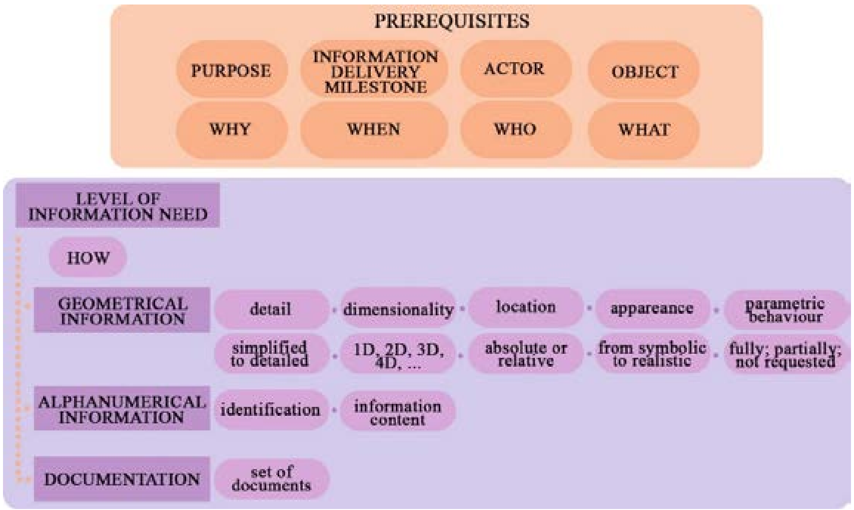

Fig. 1: Relationship diagram on level of information need.

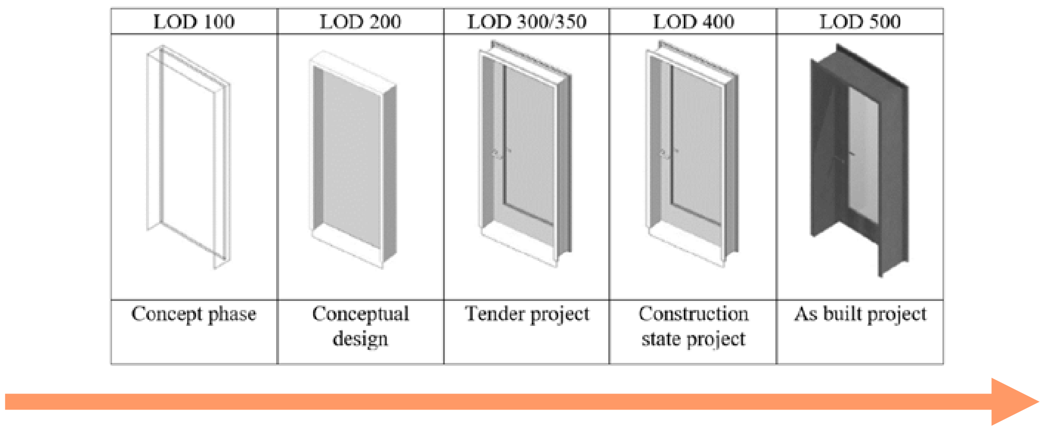

Fig. 2: Example of the concept of "continuum" associated to the detail of a door.

3. BIM ENABLED LEARNING ENVIRONMENT AND OLR CATEGORIZATION

The BLE (BIM enabled learning environment) virtual environment has the task of integrating BIM strategy and technologies into curricular activities, i.e. course modules. The BLE environment consists of the BLE Platform, that hosts pilot modules OLR and a repository that includes a Content Management System and a server that hosts BIM models and other OLR (fig. 3). The pilot modules section addresses the different pilot modules of the BENEDICT project: integrated design module, risk management module and time management module (fig 4). The repository includes a Content Management System CMS and a Data base DB for storage of OLR and students'outputs, (fig. 5). Both sections can be used by different actors, with different navigation capacities, depending on the type of user, teacher, learner, and system administrator (fig. 3).

The navigation capacity is of capital importance as depends on data and BIM object categorization. BIM models can be classified as types of models and model elements. All models are composed of model elements that have properties and attributes. Each native BIM authoring tool, as well as IFC, uses its own unique terminology to describe these components. It is therefore important to first understand what is considered an element and how elements relate to one another in order to discuss them.

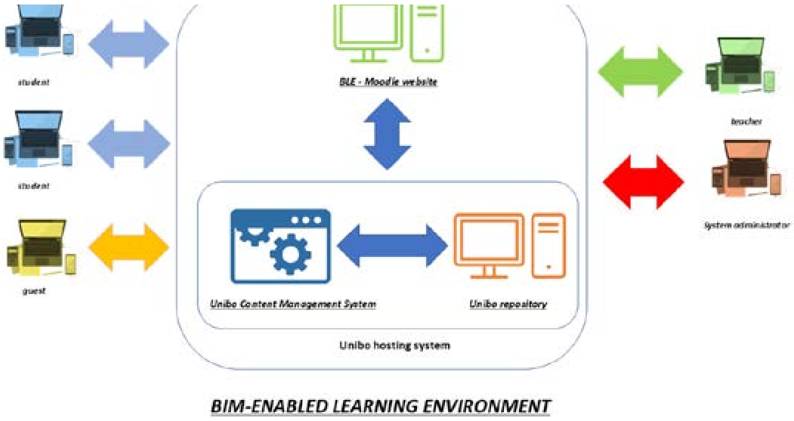

Fig. 3: BIM-enabled Learning Environment (BLE) – system architecture.

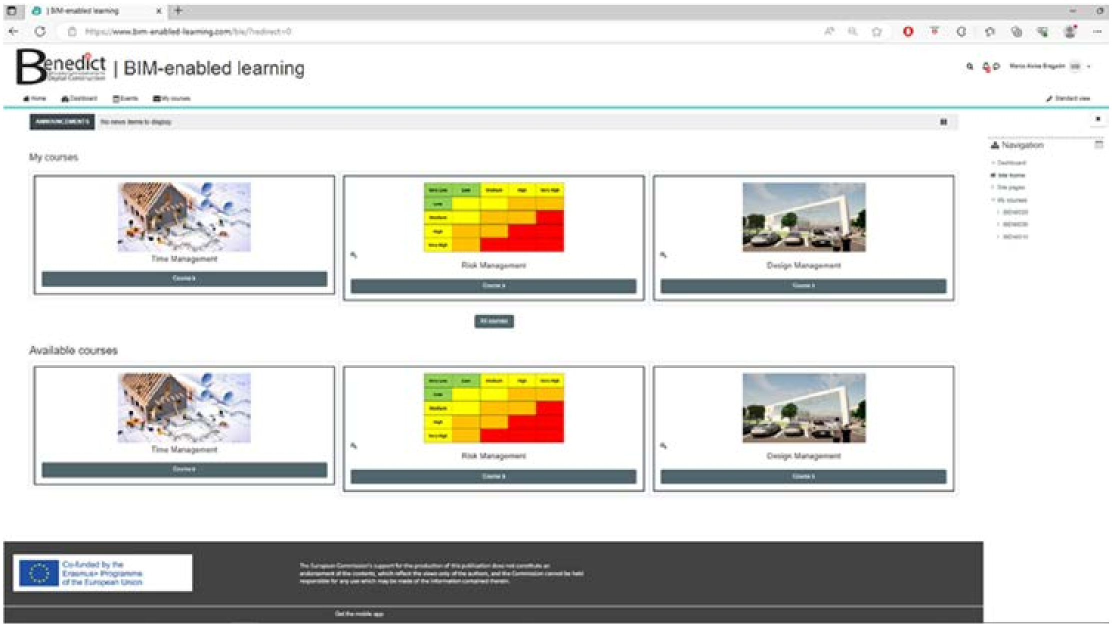

Fig. 4: BIM-enabled Learning Environment (BLE) – BLE platform.

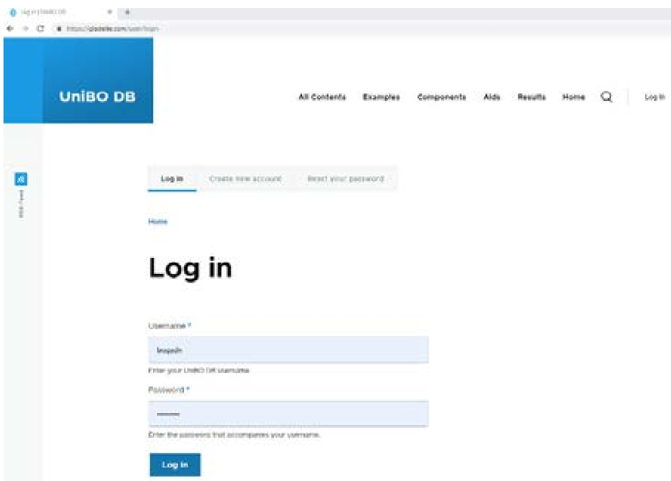

Fig. 5: BIM-enabled Learning Environment (BLE) – OLR repository.

Due to the complexity of buildings and BIMs, a simple hierarchy does not suffice to describe the relationship between model elements (US GSA BIM Guide 07). A sophisticated ontology is required to develop an understanding of how model elements may relate to one another. All the levels in the model ontology have properties associated with them, and thus the properties of one model element are associated with related model elements. A BIM ontology is an informal, semi-structured, conceptual domain ontology used for knowledge acquisition and communication between people.

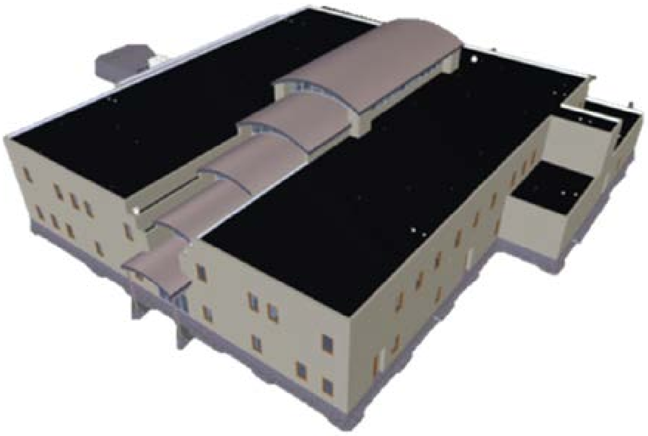

Fig. 6: Federated Model (from US GSA BIM guide 07).

A federated building information model is an assembly of distinct discipline models to create a single, complete model of the building. A federated model is a model composed of multiple linked models that contains architectural, structural, and mechanical, electrical, and plumbing (MEP) information of a building (US GSA BIM guide 07). Federation is the creation of a composite information model from separate information containers (ISO 19650 -1). A stand-alone model is a single discipline model, an information model that is a set of structured and unstructured information containers (ISO 19650 -1). The Association of General Contractor of America, AGC, in the AGC Consensus Docs 301- BIM Addendum (AGC, 2015) defines a federated model as a model consisting of linked but distinct component models, drawings derived from the models, texts, and other data sources that do not lose their identity or integrity by being so linked, so that a change to one component model in a federated model does not create a change in another component model in that federated model. A single federated model is useful for design co-ordination, clash avoidance and clash detection, approvals processes, design development, estimating and so on, but the individual models do not interact, they have clear authorship and remain separate. This means that the liabilities of the originators of the separate models are not changed by their incorporation into the federated model (fig. 6, fig. 7).

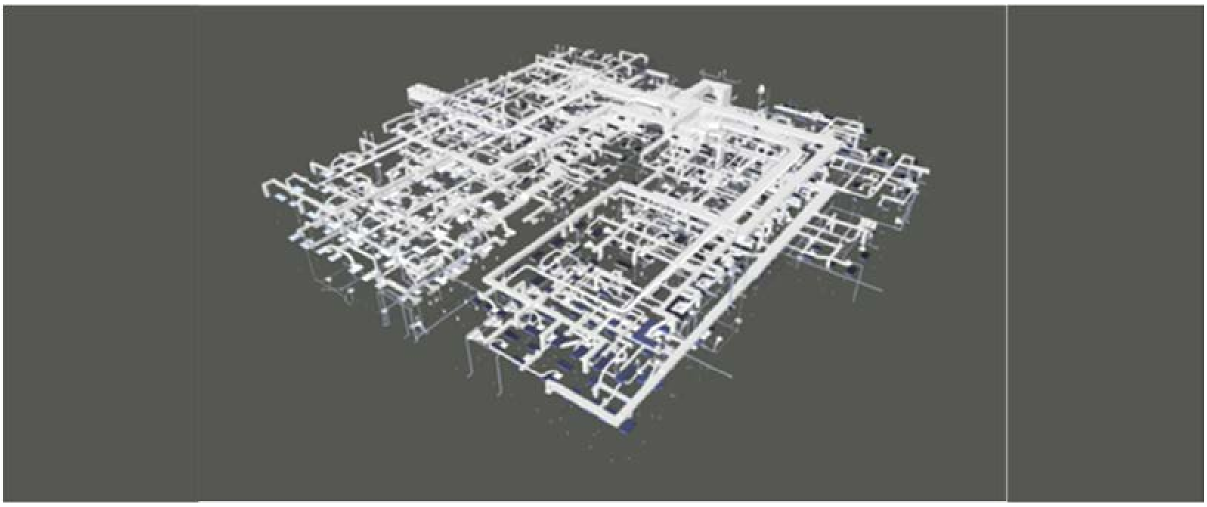

Fig. 7: Single discipline model- stand alone MEP Model of the Building (from US GSA BIM guide 07)

Categorization is of capital importance to achieve effective information management. Classification can be defined as: 'The act or process of dividing things into groups according to their type. Uniclass is based on the general structure described in ISO 12006, which promoted the use of classification classes, each of which relates to a classification need. As well as products (or objects), some of the other classes suggested by ISO 12006 are:

- Entity e.g. a building, a bridge, a tunnel;
- Complex (a group of entities) e.g. airports, hospitals, universities, power stations;
- Space e.g. office, canteen, parking area, operating theatre;
- Product e.g. boiler, door, drain pipe;
- Facilities, this combines the space with an activity which can be carried out there, for example, an operating theatre;
- Other classes can be added, such as 'system', which works very well in an MEP environment. Similarly, an 'activities' class would be very helpful for defining a range of activities which might be able to be done within a particular space, as an alternative to using the 'facilities' class.

The organization of information about construction works is of capital importance for Building Information Modelling, therefore a framework for classification is proposed by ISO 12006 standard as showed in the following tables (table 2). Information are relevant to particular stages in a building construction project, therefore, life cycle stages should be defined on a common basis. Building life cycle stages proposed by ISO standards are the following: inception; brief; design; production; maintenance and demolition. These principal stages are further decomposed to provide a meaningful set of stages for exchange requirements.

Table 2: Standard principal and decomposed life cycle stages (ISO 12006-2:2015).

Life cycle stage	**Principal life cycle stage**	**Decomposed life cycle stage**
Pre-life cycle stages	Inception	Portfolio requrements
	Brief	Conception of need
		Outline feasibility
		Substantive feasibility
Pre-construction stages	Design	Outline conceptual design
		Full conceptual design
		Coordinated design and procurement
Construction stages	Production	Production information
		Construction
Post-construction stages	Maintenance	Operation and maintenance
	Demolition	Disposal

Different classes of information are proposed by ISO 12006 standard, related to resources, as construction information, products, agents and aids; or relatated to process as management and construction process; related to result as construction complex, entity, built space, element and work result; or related to property (table 3).

Table 3: Framework for classes of information about construction works (ISO 12006-2:2015).

Class	**Classified by**
Classes related to resource	
Construction information	Content
Construction product	Function or form or material or any combination of these
Construction agent	Discipline or role or any combination of these
Construction aid	Function or form or material or any combination of these
Classes related to process	
Management	Management activity
Construction Process	Construction activity or construction process life cycle stage or any combination of these
Classes related to result	
Construction complex	Form or function or user activity or any combination of these
Construction entity	Form or function or user activity or any combination of these
Built space	Form or function or user activity or any combination of these
Construction element	Form or function or user activity or any combination of these
Work result	Form or function or user activity or any combination of these
Classes related to property	
Construction property	Property type

Table 4: Some examples of BIM classification.

<table>
<tr><th>BIM oriented classification</th><th>BIM community Classification system</th></tr>
<tr><td>• Uniclass 2015
• OmniClass
• MasterFormat®
• UniFormat™
• CoClass
• CCS
• TALO 2000
• NS 3451 & TFM
• Industry Foundation Classes
• buildingSMART Data Dictionary
• ETIM</td><td>• Language
• Type
• Project
  o Implementation
  o Research
  o Collaborative initiative
  o Other
• Category:
  o 3D – Virtual Design & Construction
  o Lean & industrialized construction
  o Planning and budgeting
  o Subcategory:
    ▪ Strategies
    ▪ Edification
    ▪ Project
    ▪ Workflows</td></tr>
</table>

The framework for classification of ISO 12006 about construction works also introduces a set of different relationships between the different classes of information. The organization model or user activity of the built asset uses the built space that is defined by a construction result, that is part of a construction complex. A construction complex is an aggregate of construction entities, composed by construction elements. A construction results is developed by a construction process that is divided in pre-design, design, production and maintenance processes. Construction process uses construction resources that can be construction product, construction aid, construction agent and construction information (ISO 12006-2:2015). Classifying data means structuring it in an agreed way so that different actors can easily find what they need and understand it. A classification system is like a common language. In BIM, classification lets people, software and machines share and use building information efficiently and accurately. Different classification systems have been developed for different types of BIM data and actors, and for different geographic areas and situations. In table 4 some other examples of BIM classification are presented.

Table 5: Metadata of BIM education Models.

Information Category	**Value Type**	**Values**	**Description**
Model Language	Text	English, Finnish, Estonian, Italian	The language(s) used in the model to describe the content
Building Type	Text	Office, Teaching, Care, Residential	Property used to describe the dominant function/use case for the facility
Discipline	Text	Urban, Architecture, Landscape, Interior Design, Structural Engineering, Building Services Engineering (HVAC and MEP), Construction Engineering, Facility Maintenance	The model discipline prepared by or for the purpose of the given discipline.
Program	Text	Small, Medium, Large	Reflecting on the size of the building, relative to its building type.
Model Categorization	Text	Mass, Room/Space/Zone, and Element models	The type of model content
Life-Cycle Stage	Text	Strategic Planning, Brief, Programming, Schematic Design, Preliminary Design, Design Development, Detailed Design, Pre-Construction, Construction, Commissioning, Hand-Over, Use, Renovation, Disassembly, Demolition	The stage of the model prepares in or for
Model Use	Text	Gather, Generate, Analyze, Communicate, Realize	Penn state classification for BIM uses
Model Maturity	Text	Initial, Defined, Managed, Integrated, Optimized	The mature of the model in any specific stage.
Geometry Maturity	Text	Symbolic, Generic, Detailed, Fabrication	Average accuracy of geometry in the model.
Model Information Reliability	Text	Preliminary, Proposed, Coordinated, As-Built	The state of the information in the model, its reliability with respect to itself and others in the process
Content Classification	Text	CCI, Uniclass, Masterformat	

As a first approach the following classification systems for Open learning resources OLR were proposed for the BLE platform: metadata, building type, size of the project, different plans, life cycle period, model categories, model functions, language/country. Metadata classification was chosen as the easiest way of OLR categorization. Many metadata of BIM models can be detected, and different categories of information can be listed in the repository for each piece of OLR. Again, a list of metadata of BIM education models is presented in table 5.

The BIM-enabled learning environment is a prototype for online BIM models repository (fig. 5; fig.8). The proposed categorization system of BIM models is based upon five categories: discipline, type of building project, life cycle stage, model use and BIM dimension (fig. 9).

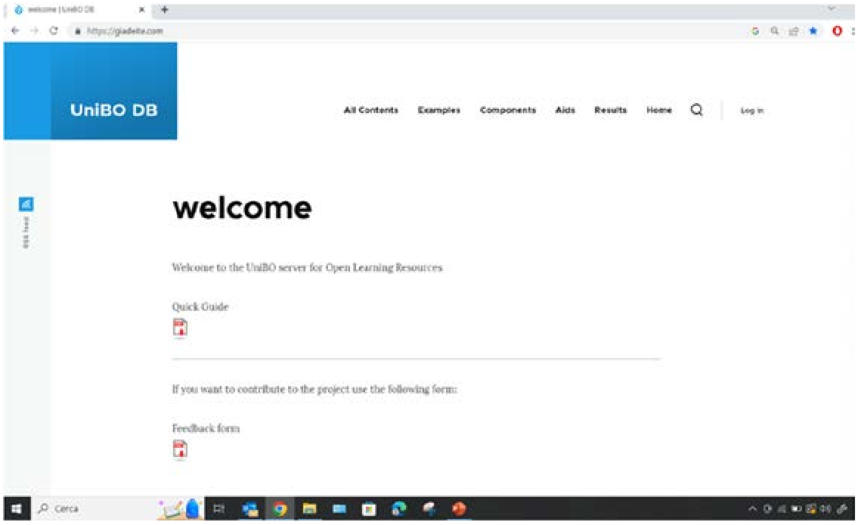

Fig. 8: BENEDICT DB – Unibo server and project data repository.

A prototype for Unibo server that host the CMS and the OLR database was developed for the proposed online BIM models repository of the BENEDICT project (http://ble.unibo.it). In the welcome page (fig. 8) it is possible to download a guideline to help end users better use the platform . From the home page, end users also could access several sub-pages including “Examples”, fully solved BIM solutions that students can use as examples, “Components” or BIM objects, “Aid” including BIM documentation, standards, project data, and “Results” where students’ outputs are stored. The repository also provides a powerful searching engine to help quickly find useful information from the repository.

4. CONCLUSIONS

In conclusion, Building Information Modelling (BIM) has become increasingly important in the field of Architecture Engineering and Construction (AEC), particularly for construction simulation and project construction management. The availability of data, reports, and information is crucial for students, teachers, and operators in the AEC industry to create BIM models. The BENEDICT project, a European Erasmus plus KA2 project, aims to develop a web-based platform for BIM teaching that is closely connected to the AEC industry. This platform, known as the BIM-enabled Learning Environment (BLE), provides a repository for BIM models, open learning resources (OLR), and students' outputs that includes a Content Manaagment System CMS and a Data Base. The CMS and the DB are freely accessible to registered users that can access OLR are essential for BIM-enabled learning processes and provide real-life project data for learners to work with. The BLE platform categorizes BIM models and elements, allowing for effective information management and knowledge transfer between different players in the AEC industry. By incorporating OLR and BIM workflows, the BLE platform enhances learning experiences and supports the implementation of BIM-based project planning and control. Ultimately, the BENEDICT project and the BLE platform contribute to bridging the productivity gap in the construction industry by promoting the use of BIM and providing a collaborative learning environment for students and future practitioners.

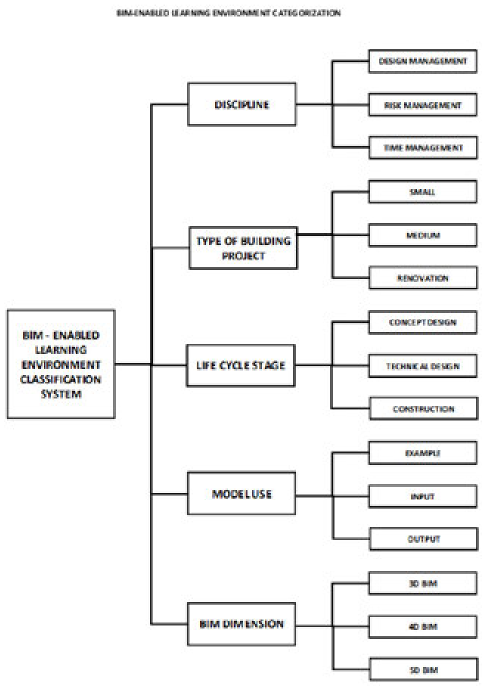

Fig. 9: BIM-enabled Learning Environment (BLE) categorization.

5. ACKNOWLEGMENTS

This research was supported by the BIM-enabled Learning Environment for Digital Construction (BENEDICT) project (grant number: 2020-1-EE01-KA203-077993), co-funded by the Erasmus+ Programme of the European Union. The European Commission support to produce this publication does not constitute an endorsement of the contents which reflect the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

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TOWARDS A DIGITAL ERA IN AEC HIGHER EDUCATION: COMBINING THEORY AND TECHNOLOGY TO DEVELOP AND DELIVER ARCHITECTURAL MASTER CLASSES

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ABSTRACT: *In recent years, technology has been playing a transformative role in the field of built environment, architecture, and construction education. It can be argued that the emergence of digital technologies has revolutionised the approach to teaching and learning in higher education in these fields. Digital technologies, such as Artificial intelligence (AI), additive manufacturing, robotics, 3D laser scanners, and Immersive Realities (IR), have played a crucial role in enhancing sustainability and efficiency in the industry. However, the opportunities provided by the use of these technologies (as a single tool or combined) in higher education and within the field of Architecture, Engineering, and Construction (AEC) are still relatively unexplored. To address this gap, this work presents a novel pedagogical framework aimed to enhance students' literacy on emerging technologies, and increase their criticality, and understanding of professional practices along with the related ethical challenges. Furthermore, to assess its effectiveness regarding the integration of immersive VR technologies in the teaching practice, a learner-centred evaluation approach is proposed, based on the collection and correlation of both qualitative and quantitative data. Concerning the former, a dedicated questionnaire is developed to collect students' subjective feedback. For the latter, a method for tracking their use of space in the virtual environment is discussed. Both the immersive pedagogical framework and evaluation approach presented in this work will be implemented in diverse architecture and civil engineering master classes in Australia and in Italy, and their comparative outcomes and validation will be the object of future joint contributions.*

KEYWORDS: *Digital and Immersive Pedagogy; Digital Technology; Architectural Higher Education; Immersive Reality, Evaluation, Questionnaire, Spatial tracking.*

1. INTRODUCTION

Over the past decades, there has been a rapid growth in urbanisation and development of urban areas across the world. This has resulted in a considerable increase in the demand for new buildings, structures and infrastructures, which, in turn, brings along a number of environmental, social and economic challenges. The nature of such challenges has become increasingly complex, so much so, that the traditional and conventional methods of construction cannot address them. Emerging technologies and digital tools have been increasingly applied in this field to address such challenges and achieve a more sustainable, safe, efficient and optimized practice (Alsafouri & Ayer, 2018; Alsafouri & Ayer, 2019; Ardito et al., 2019; Davila Delgado, Oyedele, Beach, et al., 2020; Davila Delgado, Oyedele, Demian, et al., 2020; Fazel & Izadi, 2018; Hajirasouli & Banihashemi, 2022; Hajirasouli et al., 2022; Hamzeh et al., 2019; Mandolla et al., 2019; Moon et al., 2015; Nåfors et al., 2020; Rohani et al., 2014; Valero et al., 2015). Among such technologies, Immersive Realities (IR) such as Virtual Reality (VR) and Augmented Reality (AR) have proven to be very advantageous in various areas of built environment. When considering architecture discipline and the required spatial qualities, capabilities and understanding required for it, VR seems to be a more appropriate tool to incorporate in its pedagogy, with multiple advantages (Getuli et al., 2020; Hajirasouli & Banihashemi, 2022; Hajirasouli et al., 2022; Rahimian et al., 2019). Despite the emphasis that have been made by a number of studies and scholars regarding the development of digitally enhanced and technology-integrated teaching methods (Aydin & Aktaş, 2020; Bashabsheh et al., 2019; Ceylan, 2021; Hajirasouli

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Aso Hajirasouli, Vito Getuli, Alessandro Bruttini, Tommaso Sorbi, Pietro Capone, *Towards a Digital Era in AEC Higher Education: Combining Theory and Technology to Develop and Deliver Architectural Master Classes,* pp. 266-273, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.25

& Banihashemi, 2022; Shirazi & Behzadan, 2015), a number of studies conducted by authors have identified that the current teaching and learning practices in the AEC higher education does not adequately embrace and incorporate such digitally enhanced methods and, therefore, are yet to respond to the industry's demand in this area (Getuli et al., 2020; Hajirasouli & Banihashemi, 2022; Hajirasouli et al., 2022; Pour Rahimian et al., 2019). More importantly, when developing such pedagogies, how would this affect students' perception of their education and impact their teaching and learning experience.

This study aims to provide an in-depth understanding of student's needs and requirements and, more importantly, their perception of the integration of new technologies in their courses and curriculum. For this purpose, in Section 2, a theoretical framework was developed to establish a novel immersive pedagogy. Building on the constructivist assumption of active learning for a digitally enabled pedagogy, a problem-based learning process fostered by immersive technologies is conceptualized. Furthermore, to assess the framework's effectiveness, an original mixed method for the evaluation of VR-based teaching experiences for AEC students is discussed in Section 3. This comprises a dedicated questionnaire to be administered to the students after the immersive learning experiences to collect their subjective perceptions and feedback. Complementarily, the tracking of their virtual position and its restitution in the form of contextualized heatmaps is proposed to objectively evaluate their use of the virtual environment in relation to the learning objectives. In Section 4, the implementation plan of the proposed pedagogical framework and evaluation method is then presented with reference to the architecture and civil engineering master classes which will be involved both in Australia (Western Sydney University) and Italy (University of Florence). Eventually, the discussion of the limitations and outlook of this study is provided in Section 5.

2. PEDAGOGICAL FRAMEWORK

To develop the proposed theoretical model a critical literature review was conducted, including the relevant works related to previously developed models in this area. From their analysis, constructivism philosophy emerges as the most appropriate teaching philosophy to be adapted to this framework, due to the constructive nature of immersive technologies and their implementation in teaching and learning activities. In fact, constructivism philosophy is correlated with creating and constructing new knowledge based on the learner's already existing knowledge, therefore implying an active and continuous participation in the process of learning (Behzadan et al., 2015; Behzadan et al., 2011; Biggs & Tang, 2007; Bruning et al., 1999; Lord, 1999; Luo & Mojica Cabico, 2018; Tynjälä, 1999; Von Glasersfeld, 1995). Hence, the constructivist approach was used as the principal philosophy for the developed model.

Choosing the right approach for implementing this model was the next step of this work. It is suggested that the concept of digital pedagogy does not only reflect upon using digital tools and technologies, rather, it is also about cautiously considering their effects and implications from a critical pedagogical point of view. Therefore, the decision about their integration within the teaching approach or not, depends on the desired learning outcome of a course or subject (Anderson, 2020; Barber et al., 2015; Croxall, 2013; James & Pollard, 2011). Problem-based learning approach was also used in this model as an integral part of the application and integration of immersive technologies. The selection of this approach was also due to its suitability for complex real-world situations where there is no right or wrong answer to the problem (Barber et al., 2015; Savin-Baden, 2007; Word, 2003), which is the main focus of AEC discipline and industry. This approach helps students to work collaboratively in groups, to identify the problems and gaps, and to develop solutions and knowledge, through self-directed processes (Barber et al., 2015; Savin-Baden, 2007; Word, 2003).

Eventually, immersive learning was also used as the last stage of this model. Using this method, the creation and construction of knowledge occurs through virtual immersion into a context, dialogue and/or situation. Immersion occurs in two different ways: immersion through narrative (cognitive aspects), and immersion through technological devices (technical aspects). This study focuses on immersion through technical devices, hence requires various tools and technologies, such as AR, VR, and Virtual Learning Environment (VLE). The choice of tools and technologies in this model depends upon the level of immersion required for a learning objective. VR, which is the subject of this study, is mainly being used when a fully immersive experience and a sense of presence in the virtual environment is required for the learning process.

3. IMMERSIVE VR LEARNING EXPERIENCE EVALUATION

The proposed pedagogical approach theorises the beneficial impact that the adoption of immersive visualization technologies can provide in AEC master classes. To support this claim and assess its effectiveness in upcoming case study implementations (see Section 4), an original method for the evaluation of immersive VR learning experiences is developed, considering both qualitative subjective data and quantitative objective observations. As shown in Figure 2, a questionnaire to be administered to the student after the immersive experience and divided into five inquiry areas is provided. Besides, the student's use and understanding of the virtual environment in relation to the learning objectives is evaluated with the acquisition of their spatial track during the VR experience and its sequential visualization of a BIM environment in the form of a heatmap.

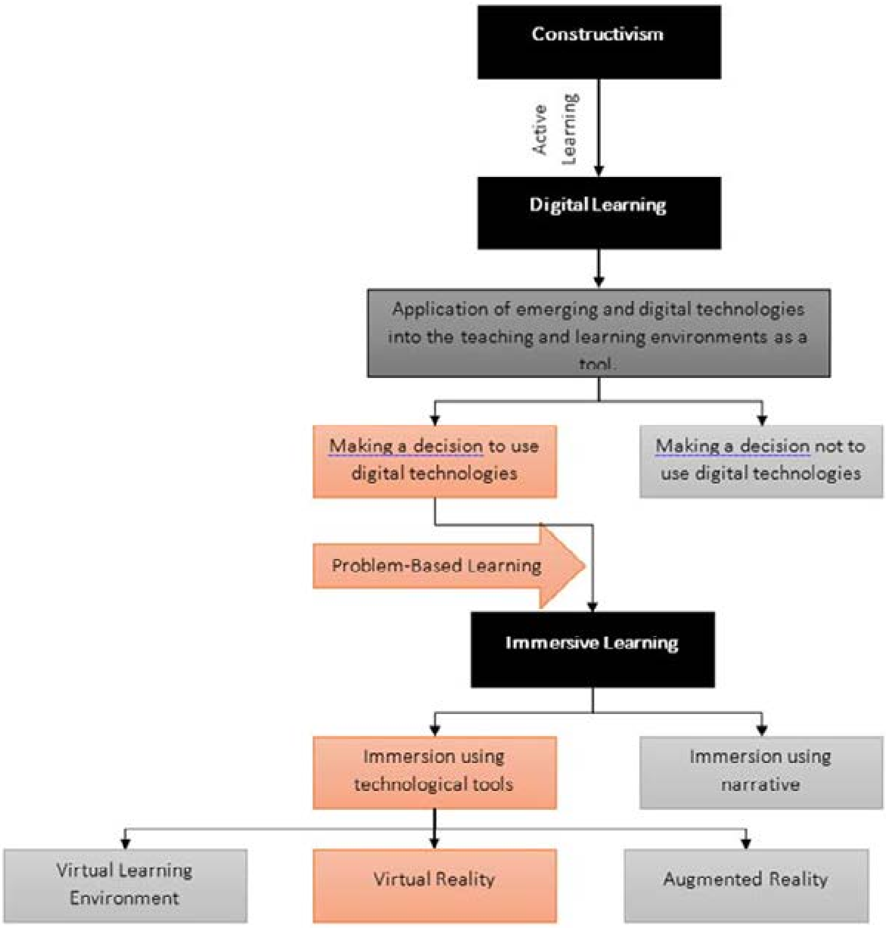

Fig. 1: Pedagogical framework designed for BIM-enabled VR-based technology application into architectural design studio.

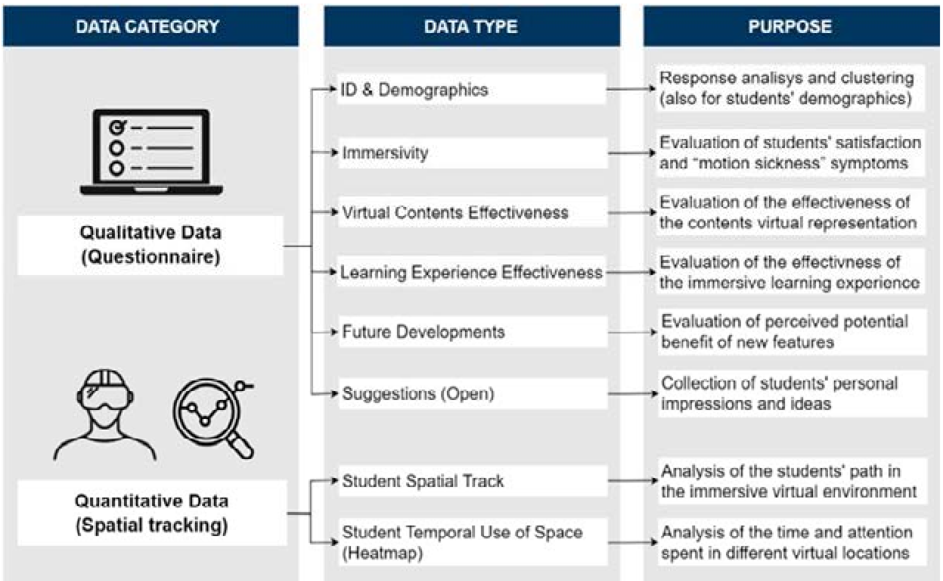

Fig. 2: Immersive VR learning experience evaluation approach – Data schema.

3.1 Post-experience evaluation questionnaire

To collect students' subjective feedback, a dedicated questionnaire has been developed to be administered directly after the immersive learning experience. First, data necessary to classify, analyse and classify the questionnaire responses based on students' demographics are collected. Then the experience is evaluated against the student's perceptions, concerning: the engagement with the virtual environment (*immersivity*); the reproduction of the virtual contents (*contents effectiveness*, e.g., graphical realism compared to the objective of the session); the gained self-efficacy and competency (*learning experience effectiveness*); the opinion on suggested additional features that could be implemented in the experience and that were currently missing (future developments). For the cited criteria the responses are collected according to a scoring system ranging from one to five, where five correspond to the maximum agreement with the statement or satisfaction with the experience. Furthermore, an open textual field (*suggestions*) is provided to enable the collection of personal remarks, impressions, and ideas, involving and empowering the student in the improvement and evolution of a learning approach based on ever-changing technologies and that will need to keep up to learners' expectations and needs to be future proof. In Table 1 the data type and the description and purpose of data collection are reported along with explanatory examples.

Table 1: Questionnaire data type description and prompt example

Data type	Description	Example
ID & demographics	Data necessary to analyse and classify the responses collected through the questionnaires with reference to the occurred immersive learning experiences, and to cluster their results also with reference to the students' demographics (anonymized). [Various]	Questionnaire ID: (Text) Immersive experience: (Text) Date: (yyyy/mm/dd) Age: (Number) Gender: (Multiple options) Course: (Text)
Immersivity	Questions related to the student's ability to get immersed in the virtual experience. They are useful for assessing how engaged the students were in the virtual world and to evaluate their satisfaction in terms of both ease of use and comfort (also related to the possible onset of symptoms of "motion sickness"). [Single rating – Likert scale]	How much did you like the experience? [min 1; max 5]
Contents effectiveness	Questions regarding the virtual representation of the learning contents, aimed at evaluating the effectiveness of the experience against the objectives of the session. [Single rating – Likert scale]	How efficiently and clearly does the content of VR help you to perceive the discussed subject better? [min 1; max 5]
Learning experience effectiveness	Questions pertaining to the overall effectiveness of the experience, aimed at investigating the actual usefulness of the immersive VR learning session compared to traditional methods, especially concerning the learning objectives. [Single rating – Likert scale]	Do you think this experience is useful in understanding the qualities of the designed spaces? [min 1; max 5]
Future developments	Questions concerning the introduction of new features (e.g., content animations, audio and visual effects, etc.) or virtual content aimed at enhancing the immersive VR learning experience through the inclusion of greater realism and/or interactivity. [Single rating – Likert scale]	Would you like to be able to grasp and interact with objects in the VR environment? [min 1; max 5]
Suggestions	Open questions to collect personal impressions and ideas from the students. [Text box]	Suggestions

3.2 Student's spatial tracking and use of space visualization

In the previous paragraph, it has been discussed how the students are actively involved in providing data for a qualitative evaluation. Here, the second, complimentary, data acquisition method is presented which is based on the objective observation of the virtual positions covered by the students throughout the experience. In turn, this involves capturing the position of the student in the VR environment during the entire course of the simulation in order to analyse their actual use of the tridimensional space. For this purpose, the student's virtual position shall be recorded with a data acquisition rate of at least 1 Hz. The 3D point sequence resulting from this process shall be transferred in a BIM environment and converted for the generation of heatmap visualization, within which the position of the student is represented, weighted by the time spent, with a colour gradient. In this way, the relevance of different areas of the experience can be evaluated based on the time spent in certain virtual locations by the students. As with the questionnaire's development, the student spatial tracking and visualization procedure to be performed during the learning experience is explained with reference to the collected data type in Table 2.

Table 2: Student's spatial tracking and use of space visualization characteristics

Data type	Description	Example
ID & demographics	See Table 1.	See Table 1.
Learning experience duration	The duration of the experience from start to finish, excluding a possible tutorial or time required to the student to get used with the immersive VR system and controllers. This is necessary to allow for the later heatmap visualization of the student use of the virtual space weighted on the overall elapsed time. [time in seconds]	Duration: (number) sec
Student spatio-temporal track	The student position in the virtual environment is collected as 3D point with 1 Hz frequency. The corresponding spatial track is then graphically represented against a model of the experienced environment (e.g., BIM model) both as a 3D path (polyline) and with an heatmap representation, with the colour gradient weighted on the time spent in a certain location.	Colour gradient representation of the student's followed path (weighted by time) [min. green, max. purple]

4. FRAMEWORK IMPLEMENTATION PLAN

The theoretical approach of this paper is built upon previous research projects, undertaken by authors in Australia and Italy, to create an innovative approach and prototype protocol for the design, delivery and evaluation of a number of subjects for AEC students in higher education, based on an interactive and immersive learner-centred approach. The outcome of this work will be implemented in a number of course subjects at the University of Florence, Italy and Western Sydney University, Australia. The nominated subjects for the implementation of this model are reported in Table 3.

Table 3: Immersive VR learning approach for AEC higher education - Implementation plan

Institution	Course (Academic Year 2023/2024)	Expected attendees
Western Sydney University, Australia	• Advanced Design Communication (ARCH7007) • ARCH7015 Practice Research Studio Civic (ARCH7015)	50 50
University of Florence, Italy	• BIM and Information Modeling of the Construction Process (B028836) • Design and Safety of Workplaces B030584 (B063)	50 50

The implementation of the proposed pedagogical model will engage the students in providing indications and opinions regarding the environment in which they are exploring and studying. This approach will help with validating both the pedagogical framework, as well as, the designed environments, by gathering the user's experiences and observations. This, in turn, will assist in enhancing the entire framework developed in this study. For this purpose, and according to the principles discussed above, a prototypical questionnaire implementation comprising 16 questions has been developed and is represented in Figure 3.

In addition to the questionnaire, a prototypical implementation of the student spatial tracking restitution in form of heatmap is proposed in Figure 4. As it can be seen, the more relevant areas of the virtual environment for learning purpose could straightforwardly be inferred based on the time spent, providing useful information in the development of further immersive teaching material (e.g., virtual environments).

Student Data

ID:	
Age:	
Course:	
Gender:	

	Questionnaire	min - max
Immersivity	1) Did you enjoy the experience?	1 2 3 4 5
	2) Were you comfortable during the experience?	1 2 3 4 5
	3) Was it easy to use the viewer and controller?	1 2 3 4 5
	4) Did it bother you not being able to see your body in the virtual world?	1 2 3 4 5
Contents' Effectiveness	5) Are the signal arrows helpful in figuring out where to go?	1 2 3 4 5
	6) Does the virtual building spaces sufficiently replicate the real one?	1 2 3 4 5
	7) Did you need less time to understand the content displayed in VR compared to a face-to-face power-point presentation?	1 2 3 4 5
	8) Were your learning skills affected by the VR experience?	1 2 3 4 5
	9) Do you think this experience can replace the role of the educator?	1 2 3 4 5
	10) Do you think this experience is useful in getting to know a subject before it is explained to you by an educator ?	1 2 3 4 5
Learning Experience's Effectiveness	11) Do you think this experience is useful in understanding the building and its technological aspects?	1 2 3 4 5
	12) Is this type of learning useful for an inexperienced student?	1 2 3 4 5
	13) Is this type of learning useful for a student without any knowledge on the subject?	1 2 3 4 5
	14) Do you prefer to interact with an avatar or a teacher?	1 2 3 4 5
Future Development	15) Would you like to listen audio explanations of the virtual scenarios?	1 2 3 4 5
	16) Would you like to be able to interact with virtual objects?	1 2 3 4 5

Suggestions

Fig. 3: Immersive VR learning session evaluation questionnaire – Implementation prototype.

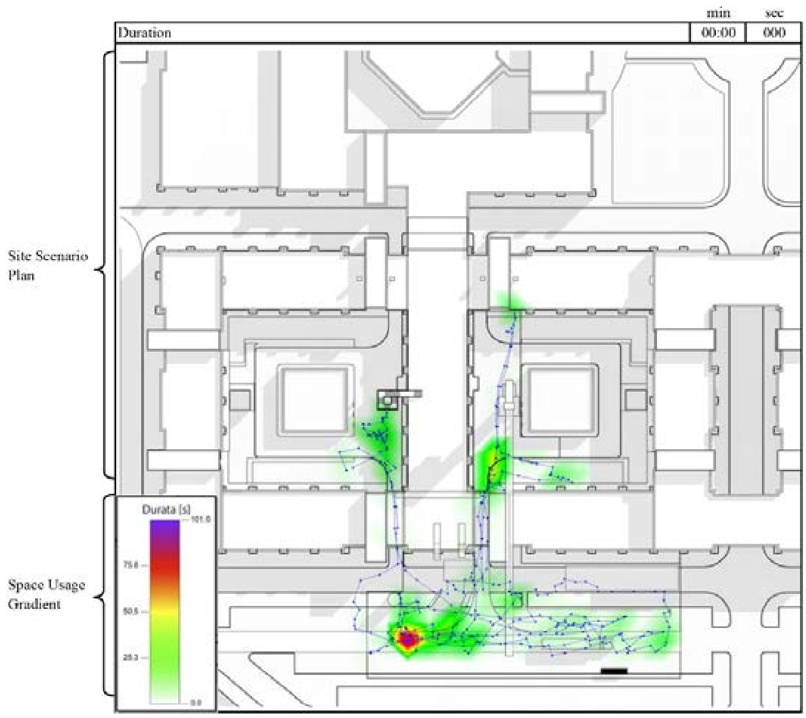

Fig. 4: Student spatial track heatmap representation – Implementation prototype

5. CONCLUSIONS

This study, which was a successful collaboration between University of Florence and Western Sydney University aimed to provide a comprehensive understanding of student's perception and demand of the newly developed pedagogical framework. This framework aimed to create a more engaging learning environment, while responding to the industries needs and requirements, and prepare students for the future of their careers in AEC. To achieve this, this study was developed in two stages. In stage one, a qualitative approach was used to develop a novel pedagogical framework, based on the constructivism method, followed by a problem-based approach and immersive learning method. To test the effectiveness of this developed model and student's perception of it, a mixed-method approach was used to develop an in-depth questionnaire. Furthermore, a contextualized heatmap recording is accompanying the developed survey to ensure the robustness of the results of this study.

The outcome of this research will be tested internationally at the architecture and civil engineering master classes which will be involved both in Australia (Western Sydney University) and Italy (University of Florence) in early 2024. The outcome of the experiment will form another joint publication and collaboration between the two institutions.

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A FRAMEWORK FOR REALISTIC VIRTUAL REPRESENTATION FOR IMMERSIVE TRAINING ENVIRONMENTS.

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ABSTRACT: *As mixed-reality (XR) technology becomes more available, virtually simulated training scenarios have shown great potential in enhancing training effectiveness. Realistic virtual representation plays a crucial role in creating immersive experiences that closely mimic real-world scenarios. With reference to previous methodological developments in the creation of information-rich digital reconstructions, this paper proposes a framework encompassing key components of the 3D scanning pipeline. While 3D scanning techniques have advanced significantly, several challenges persist in the field. These challenges include data acquisition, noise reduction, mesh and texture optimisation, and separation of components for independent interaction. These complexities necessitate the search for an optimised framework that addresses these challenges and provides practical solutions for creating realistic virtual representations in immersive training environments. The following exploration acknowledges and addresses challenges presented by the photogrammetry and laser-scanning pipeline, seeking to prepare scanned assets for real-time virtual simulation in a games-engine. This methodology employs both a camera and handheld laser-scanner for accurate data acquisition. Reality Capture is used to combine the geometric data and surface detail of the equipment. To clean the scanned asset, Blender is used for mesh retopology and reprojection of scanned textures, and attention given to correct lighting details and normal mapping, thus preparing the equipment to be interacted with by Virtual Reality (VR) users within Unreal Engine. By combining these elements, the proposed framework enables realistic representation of industrial equipment for the creation of training scenarios that closely resemble real-world contexts.*

KEYWORDS: *Digital twin; 3D reconstruction; Virtual reality; Laser scanning; Photogrammetry; Training simulation; Unreal Engine.*

1. INTRODUCTION

In recent years, the increased availability of mixed-reality (XR) technology has spurred the exploration of virtual reality training environments, which showcase their immense potential in enhancing training effectiveness across various domains(Abulrub et al., 2011). By reducing expenditure associated with travel and physical resources, safety training that has been delivered via virtual methods is predominantly more cost-effective than non-virtual alternatives, without sacrificing training effectiveness (Adami et al., 2021) (Stefan et al., 2023).

Virtual Reality (VR) can present us with realistic replications of real-world situations with a high degree of accuracy, and immersive virtualised training scenarios can significantly improve participant engagement when compared to equivalent training using conventional methods (Sacks et al., 2013). Trainees presented with a virtual environment can engage with high-risk scenarios without actual danger. The elimination of risk fosters confidence and risk-free experimentation, which has a significant positive impact upon post-training technical proficiency (White & Jung, 2022). Regarding the attitude of trainees towards professional learning content, Loosemore and Malouf (Loosemore & Malouf, 2019) suggest that there is “a need to adapt safety training to create more emotional connection” between the trainees and their learning within the construction industry, and that “New technologies such as virtual reality may be useful this context since through [life-like] immersion in the work environment and simulation of workplace accidents, they are able to create a stronger emotional connection with the subject matter.” This suggestion is supported by Newton, Wang and Lowe (Newton et al., 2015) who find that “incongruously, results indicate that user’s reporting their experience of virtual reality score that experience higher in presence terms than users experiencing the physical world,” indicating that virtual experiences may be more emotionally engaging and more impactful for trainees than real-world experiences alone. This calls us to re-examine our approach to training and education as we begin to see XR technology as an effective tool to enable trainees to connect theoretical knowledge and practical application.

The standard of these simulations is influenced by the quality of virtual representation. High-fidelity 3D illusions bridge the gap between physical and digital environments and enhance the task-oriented performance of the

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Caolan Plumb, Farzad Rahimian, Diptangshu Pandit, Hannah Thomas, Nigel Clark, *A Framework for Realistic Virtual Representation for Immersive Training Environments.*, pp. 274-287, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.26

trainees (Slater, 2009) and so highly-realistic virtual assets may improve the effectiveness of the virtual experience.

1.1 3D Scanning Methodologies

To elevate the authenticity and realism of virtual training, exploring 3D scanning methodologies (such as photogrammetry and laser scanning) present exciting possibilities as potential solutions for highly realistic representation within VR scenarios. By employing advanced 3D scanning technologies, we can capture with accuracy the dimensions and intricate surface details of real-world equipment and environments. After sufficient data has been captured with scanning hardware, the data will be manipulated through a pipeline of various specialized 3D modelling software to create a mesh that may be rendered by a games engine.

There are practical challenges associated with the application of 3D scanning techniques which must be addressed, such as site-access for data acquisition, followed by noise reduction and asset optimization. To conduct the training, the user will be expected to manipulate the asset, or parts of the asset, using virtual reality hardware. Therefore, not just aesthetic accuracies, but realistic interaction and functionality will also be essential. Equipment which has independently moving components will have to be separated into dynamic and static bodies to facilitate independent movement and interaction within the virtual environment.

1.2 Goals of this Article

Our effort to establish a framework that adheres to industry best practices has been in collaboration with The Faraday Centre, recognised for their expertise in electrical engineering training. Ordinarily, The Faraday Centre delivers training using out-of-service switchgear that has been refurbished or donated to the Centre, so that trainees can receive hands-on practical training with switchgear up to 33kV. A significant challenge presented by electrical engineering equipment is that there are high costs associated with the newer, higher-voltage switchgear, thus making their acquisition impractical. A virtual training environment (VTE) offers a cost-effective alternative to simulate operation of this high voltage equipment for training purposes. Our data-driven approach hopes to ensure that the virtual representations closely mirror their physical counterparts.

Therefore, we believe that establishing a framework encourages the integration of virtual technologies for industrial training scenarios. Our objective is to provide insights into the scanning methodologies, challenges faced, and available solutions in capturing the details of real-world environments, equipment, or other assets. To achieve this, this paper will review the current technology and methodologies used to emulate real-world equipment and their processes within a virtual context. Drawing inspiration from methodologies employed in data-driven digital twinning pipelines (Pan et al., 2022), both photogrammetry and laser-scanning applications are integrated within this framework and their compatibility with the development of contemporary professional training for high-risk environments is discussed. The framework proposed is capable of systematically addressing each obstacle, thereby ensuring a seamless transition from physical equipment to the creation of highly realistic virtual training environments.

This paper is organized as follows: **section 2** will look review production pipelines, methods and motives for the creation of such data-driven virtual assets. **Section 3** presents an overview of the technology required to scan a 3D object and recreate it as 3D virtual asset. **Section 4** will report the framework we have developed as a solution to the challenges presented when developing realistic VR-ready assets from high-voltage switchgear scan-data.

2. METHODS FOR REALISTIC VIRTUAL REPRESENTATION

Virtual representation encompasses the creation of digital reconstructions of real-world subjects, including those with glossy surfaces like switchgear equipment. Specular (mirror-like) reflections can challenge 3D data capture methods like laser scanning and photogrammetry, reducing the usefulness of output models (Frost et al., 2023), therefore we will review approaches designed to address issues associated with capturing accurate data.

Another challenge involves minimizing the computational power required for rendering our results in a real-time application. Two viewpoints (one for each eye) must be rendered, making VR susceptible to difficulties with framerate, which will be affected negatively by superfluous model complexity. Therefore, our review will be extended to provide an overview of various methods to clean and simplify our results.

2.1 Photogrammetry

Photogrammetry is a 3D surveying and modelling method which has the major advantage of being low-cost, portable, flexible and is capable of delivering highly detailed reconstructions. Three-dimensional information about objects or environments is obtained by analyzing a dataset of two-dimensional photographs.

Photogrammetry relies on the identification of feature points on or within the object being scanned. Areas of the subject with aspects like colour variation, surface imperfections, or details such as dust and grime must be adequately captured to be reconstructed. Significant overlap across multiple images in the dataset is crucial to ensure an ample supply of contrasting, unique points. Observed similarities across images is used to reinforce the confidence of the photogrammetry software in determining the 3D positions of each point. Available photogrammetry software options are discussed in Section 3.

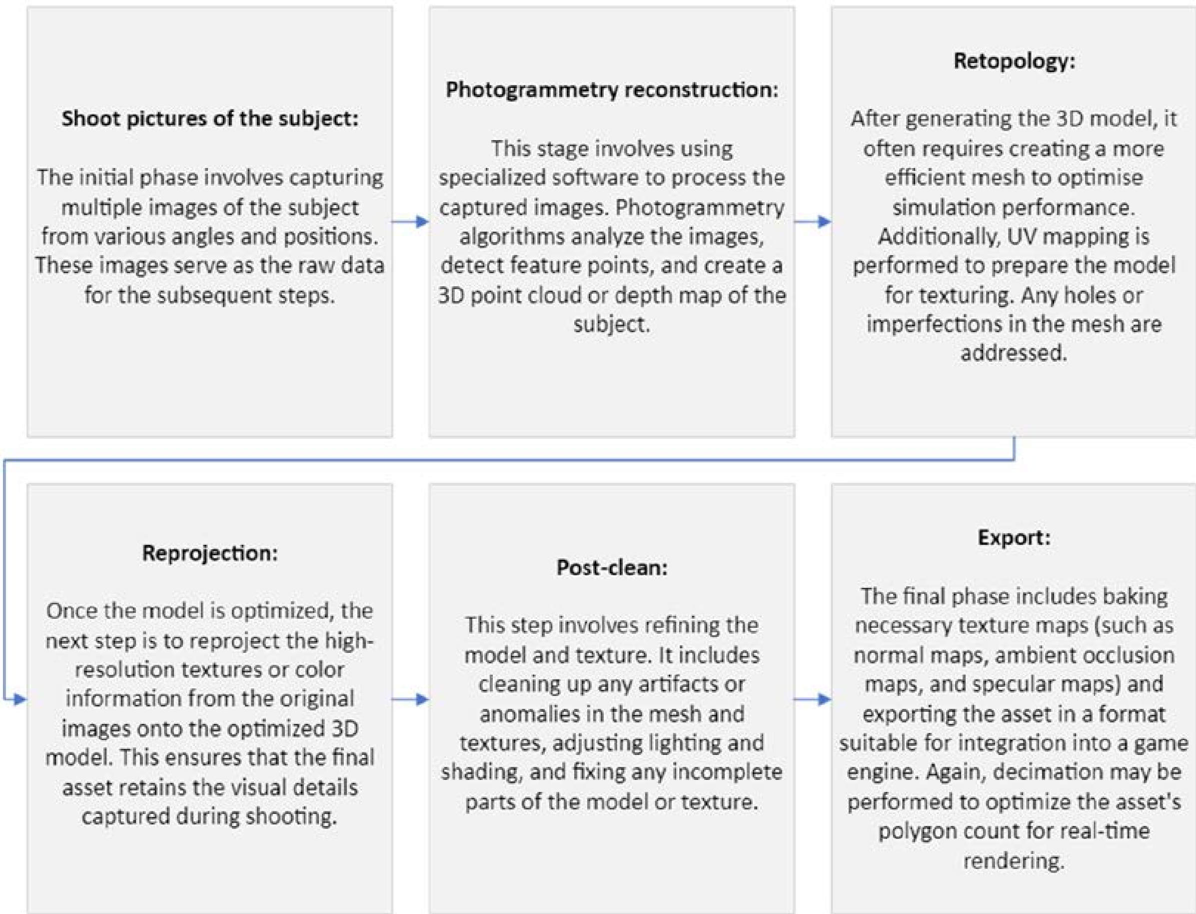

Fig. 1: A Photogrammetry process diagram showing an overview of the various stages from data capturing to a simulation-ready asset

The accuracy of camera alignment and the quality of the created asset is determined by consistency across the data obtained from the input images. In cases where the object's surface lacks distinctive features, challenges arise in achieving accurate surface reconstruction. According to Schiach, the objects best suited for automated image-based 3D reconstruction methods feature amorphous geometries, structured surfaces, numerous edges, and exhibit inhomogeneous colouring. Objects that yield poor or no results typically have monochrome, translucent, reflective, or self-resembling surfaces (Schaich & Fritsch, 2013). Dark materials, insufficient lighting, and changes in lighting can all have detrimental effects on the image quality and may prevent the photograph from registering as correctly aligned. Methods we may employ to optimise the conditions in which we capture data include strategic distribution of light sources to eliminate shadows, applying a coat of spray to make the surface more responsive to scanning, cross polarisation techniques, or by using some combination of these methods (Noya et al., 2015; Porter et al., 2016).

2.1.1 Capture methods

To capture a static object, the photographer moves around the subject, taking multiple pictures from various viewing angles. Collecting every angle may be made difficult if the object is quite large and/or positioned inconveniently for photo-scanning purposes, meaning a complete scan may be impossible without repositioning the object. For the feature detection algorithms to run correctly, the features of the input images must remain consistent. Therefore, if we wish to reposition the object, we must take the additional step of separating desirable features of our subject from undesirable inconsistencies from background visual information. Typically, this involves manually applying masks to each input image, a potentially time-consuming process (Farella et al., 2022), even with expediating background removal features like semantic segregation (Chen et al., 2017; Kang & An, 2021; Ronneberger et al., 2015).

Alternatively, a camera configuration with strategic lighting can be set up to automate the masking process. Background interference may be avoided by ensuring the scanned object is well-lit against a dark, featureless background. This allows for the target to be rotated and repositioned in front of a camera which may remain fixed, providing sufficient captured data from various viewing angles, without the feature detection algorithms being disrupted by undesirable information. The effect of this method may be improved by strengthening the lighting of the foreground to heighten the contrast between the foreground and background. This lighting can be provided in different ways, the object may be homogenously lit with LEDs from various angles, or a piece of equipment such as a ring light may be employed; both may sufficiently eliminate shadows.

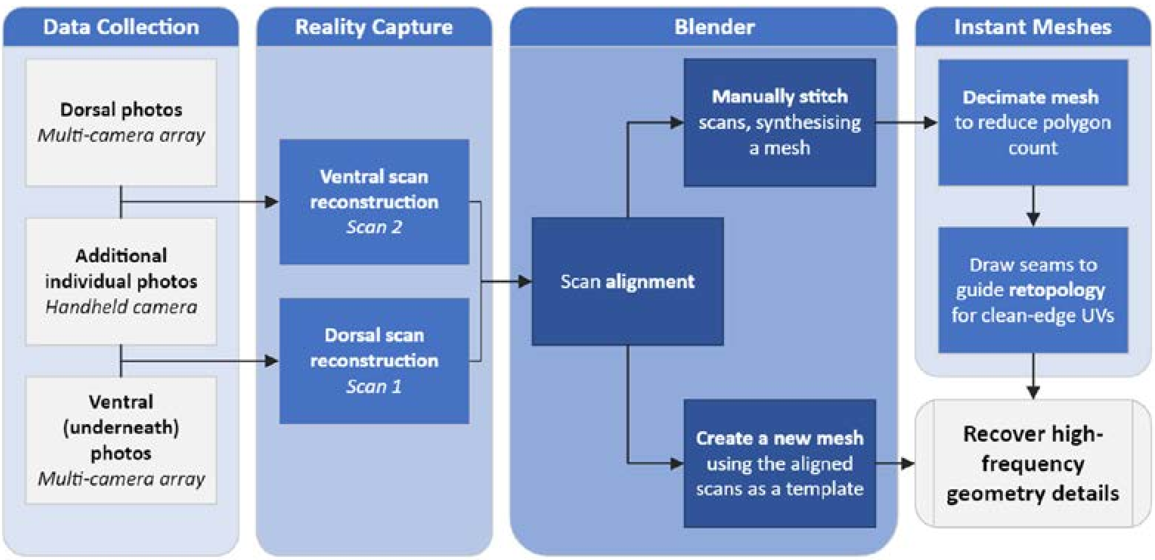

Fig 2: A flowchart describing the process used to create a clean asset from a photogrammetry reconstruction using a multi-camera array to capture a turtle (Bot et al., 2019). The software used is included. Recovering high-frequencies geometry details will be expounded upon in Section 2.3.

To capture dynamic objects, a single camera is unsuitable as it presents a high risk of capturing inconsistent data due to movement of the subject. Therefore, a multicamera array is used, which typically consists of 4 to 30 cameras on tripods or metal rods, with all of them pointing towards a central area. This "rig" of specially calibrated lights and cameras permits efficient and simultaneous data capture from various angles to ensure consistency across source images. An alternative method is the use of synchronized video with a common motion (e.g., a clapper or a ball drop in view of all cameras). Figure 2 shows the methodology employed by (Bot et al., 2019) when using a multi-camera array to scan and create and asset that captures the likeness of a turtle.

2.1.2 Cross polarisation and reflectance acquisition

VR is capable of simulating realistic lighting and accurate material properties. Reflectance acquisition techniques are used to measure an object's reflectance properties under varying lighting conditions. One such approach using polarisation techniques is outlined by figure 3, below. Numerous images are taken with different lighting conditions to sample the appearance of specular highlights under a dense sampling of lighting directions, which can be data-intensive and time-consuming, particularly when dealing with highly specular surfaces.

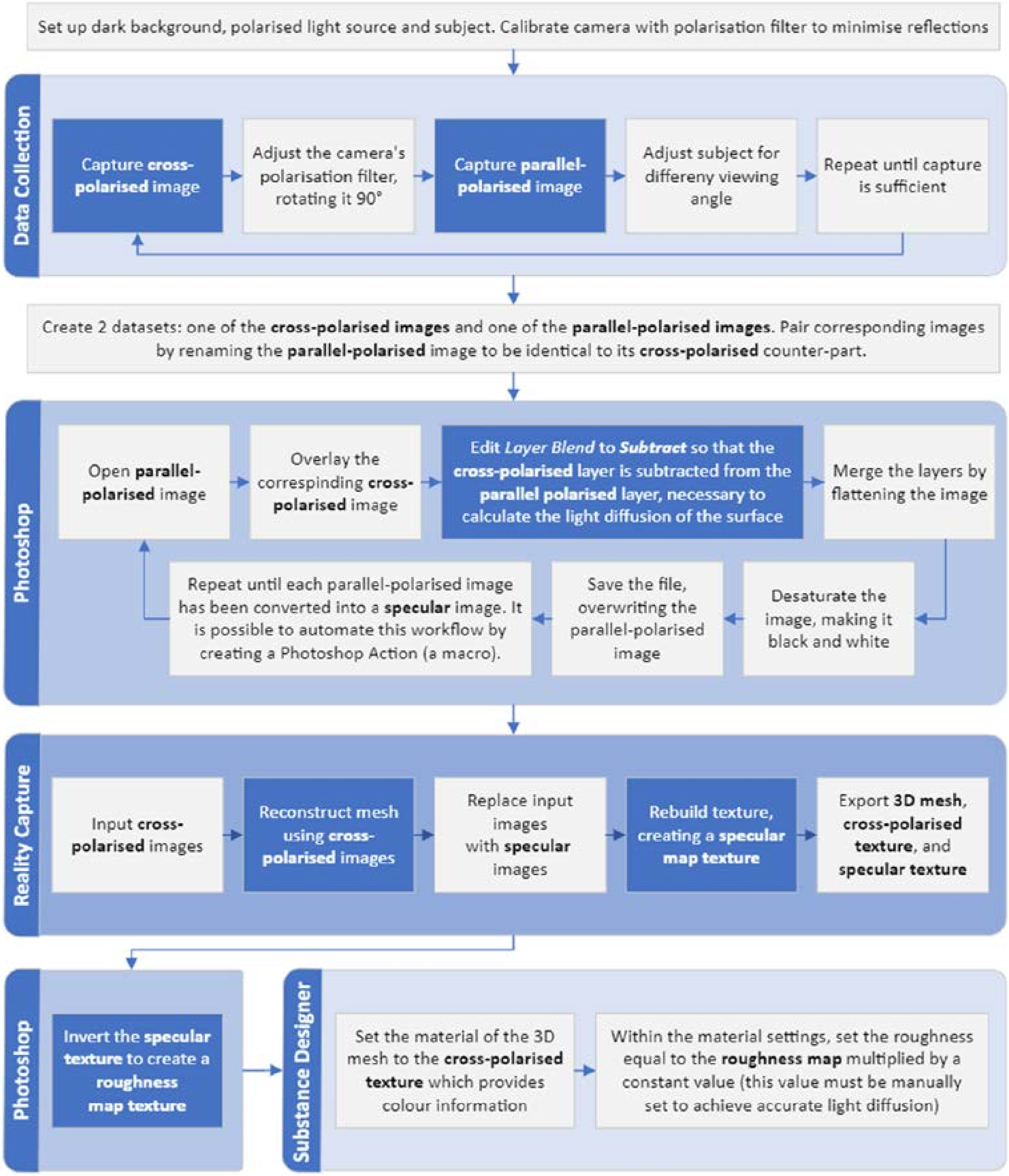

Fig. 3 A flowchart showing an overview of the data processing required to prepare what information is collected in a cross-polarisation method (Frost et al., 2023) to acquire reflective data, including the software employed.

Cross polarisation methods produce an image where most of the specular data is removed using two orthogonal polarisation filters. One filter is placed on the camera lens, and the other is a polarising film positioned in front of the light source to illuminate the target with polarised light. Cross-polarised images are highly effective for photogrammetry reconstruction as they minimise disruptions caused by reflections (Frost et al., 2023).

The polarisation filter on the camera lens can be adjusted to be parallel rather than orthogonal, thus producing a corresponding image which preserves specular information. Subtracting the cross-polarised image from the parallel-polarised image yields a specular image. Collecting specular images from multiple camera positions allows us to create a specular map by replacing the cross-polarised data with the specular data during the reconstruction process. This map represents the reflectivity of the object's surface at different locations on the mesh. However, achieving this in uncontrolled environments, where ambient lighting is beyond our control or with large equipment that requires camera movement, can be challenging and result in inconsistencies.

2.1.3 Colour correction

To ensure the accuracy of the model texture, especially for its use in a games engine for simulation, managing lighting conditions is crucial. If lighting affects the color of the captured images, a Look-Up table (LUT) can be applied to the input images to correct their colour accuracy. Software like Houdini (SideFX, 2022) or Photoshop (Adobe, 2022) can generate this LUT from an image of a colour checker taken at the site under the same lighting conditions as the photos, and then batch process the input images, correcting colour information.

Most games engines have their own lighting systems. Depending on the 3D objects being rendered, most 3D games engines simulate realistic shadows for objects in relation to in-simulation light sources. These shadows can be dynamically calculated at runtime, adjusting with user interactions or object movements. In some cases, shadows might be baked into the scene if they are not expected to change. If shadows were captured in the source photos due to non-flat lighting during image capture, they could inadvertently become part of the object's texture information. To address this, the shadow information should be removed. This can be achieved by opening the texture data from the UV maps in software like Photoshop, where adjustments can be made to minimize or eliminate the shadows. This process homogenizes and evens out the lighting affecting the texture, allowing the games engine's lighting to handle shadows appropriately.

2.2 LiDAR

In recent decades, point clouds obtained through light detection and ranging (LiDAR) have become a significant data source for various mapping applications within the photogrammetry, remote sensing, and cultural heritage communities among many others (Leberl et al., 2010) (Wang et al., 2018). There are two primary LiDAR methods to consider, laser scanning and structured light scanning. Both make use of time-of-flight (ToF) calculations, the scanner can determine the distance and create a point cloud of the object's surface. Their advantages include their noninvasive nature, high precision, and interoperate easily with supporting software.

Aerial laser scanning (ALS) and Terrestrial laser scanning (TLS) are two examples of long-range scanning methods that rely on laser beam emission. The emitted lasers can reflect off of surfaces up to 130 meters away, and can be used to scan large objects such as airplanes. The Focus3D S120 (FARO) is a laser scanner employed by (Wang et al., 2019) as described in figure 5, so this method may be fit for our purposes, however, long-range can be more expensive and may require more time for data processing.

Structured light scanners project patterns of light (such as grids or stripes) onto the surface of an object. The deformation of these patterns on the object's surface is captured by the scanner's cameras. The distortion of the patterns is then used to calculate the 3D coordinates of the object's surface points. Cui, Tao and Zhao acknowledge that the 3D light-section reconstruction method (depicted in figure 4) is a common and applicable way to obtain point cloud data for the needs of 3D reconstruction potential accurate to the millimeter. Structured light scanners are generally faster than laser scanners and are well-suited for capturing medium-sized objects with moderate to high surface details.

However, like photogrammetric methods, structured light scanners struggle with reflective, transparent, or homogenous surfaces. Their accuracy can vary based on the complexity of the object's surface; for example the performance of these scanners suffers when there is a distinct lack of points of interest on the surface, as it makes it difficult for the algorithms within the software to accurately track the lasers position frame by frame. Consequently, the scanner will “slip,” leading to inaccuracies in scanning surfaces. We may mitigate some of these issues by scanning the surface multiple times, or by introducing additional features to aid 3D registration.

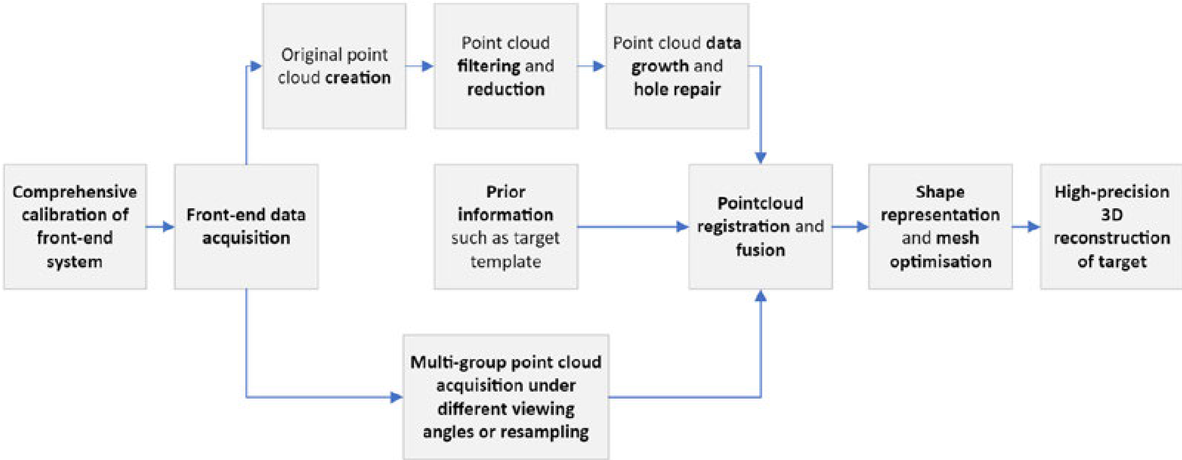

Fig. 4 A process diagram showing the light-section method for a structured light scan. (Cui et al., 2021)

2.3 Model Synthesis for Virtual Reality

To achieve realistic virtual representation, it's crucial to capture high-frequency details. However, this often results in high-polygon count 3D models generated by scanning methods, which can slow down real-time simulations, especially in virtual reality. Mesh decimation helps reduce the complexity by simplifying the mesh to a target polygon count, although some detail is lost in the process. As depicted in figure 2, in cases where the scan data has inconsistencies, further reconstruction and cleaning with 3D editing software might be necessary. Alternatively, the scan can serve as a reference for creating a new, more accurate mesh.

High-frequency detail can be restored by generating normal maps from the complex mesh, which are used to create detailed shadows and highlights. Unwrapping the mesh's topology into UVs is required to store this data as a texture file. Specialised software such as InstantMeshes as mentioned in (Bot et al., 2019) or similarly specific tools like those of Houdini (SideFX, 2022) called Sidefx Labs which contains the AutoUV as used in (Triantafyllou et al., 2022). After retopologising the mesh, any available texture information can be reprojected. If the captured

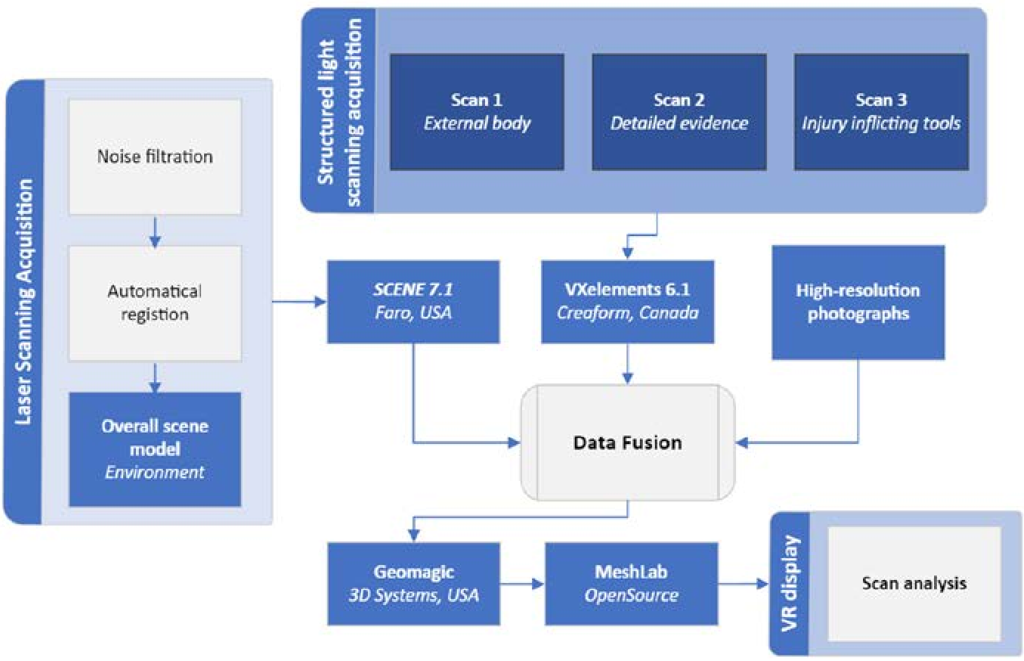

Fig. 5: A diagram showing an overview of methods being used to reconstruct a detailed environment for VR (Wang et al., 2019)

texture data is insufficient, libraries like Quixel Megascans provide high-quality textures for approximating the surface material.

One example (Alexander et al., 2009), involves the use of a stereo-camera rig with strategically placed lights. This rig is calibrated to capture multiple images simultaneously, each providing various lighting information: cross-polarized, parallel-polarized, and spectral line measurements for diffuse albedo, specular albedo, and 3D geometry, respectively. To aid data calibration, makeup dots on the target are used, ensuring they don't obstruct data while allowing precise realignment. By contrast. (Wang et al., 2019) merge laser scan point clouds using registration software. Ground control points (GCPs) and other scene features' known locations are used to combine scan data, creating a comprehensive indoor environment reconstruction. Additional scans made with structured light scanners add more detailed information to specific areas of interest for analysis.

Once the data from these various methods has been combined, the next key challenge lies in effectively separating these components to enable interaction within the virtual environment. Advanced VR interactions, characterized by direct manipulation, diverse input devices, and high degrees of freedom, demand the division of the unseparated scan-data model into distinct, potentially modular components. 3D modeling software will play a pivotal role in separating the components for independent simulation of their interactions.

For training purposes, equipment behaviors will also require virtual recreation. While the best approach is to have firsthand expert demonstrations of the equipment, this is often not feasible due to factors like high risks and limited accessibility. In such situations, an alternative approach is to attach recording equipment to a professional who can perform the necessary operations. This recorded footage can then be used as a reference for replicating the equipment's behavior in a virtual environment.

3. TECHNOLOGY

A standard asset creation pipeline involving scanning processes will require several pieces of hardware to collect data, with the appropriate software to process the information. We will also consider hardware and software required to develop functionality and render the equipment as interactable models within a VTE. The most effective solutions will be discussed below.

3.1 Software

Each step in this process necessitates specific software tools. Initially, images must be prepared for alignment, followed by running photogrammetry algorithms to construct textured models from these images. The subsequent phase involves processing the data obtained through 3D scanning to create a 3D model that faithfully represents the physical geometry of the scanned subject. This model must be optimized for seamless integration into a games engine for virtual interaction, and various texturing solutions will be evaluated. It's common to encounter multiple software options for each stage of the scanning process. Some software packages bundle applications to be used in tandem with diverse workflows, and open-source alternatives may also be available. (see Table 1). For the software upcoming to be listed, the minimum processing requirements would be a 2GHz CPU and 16GB or more RAM.

Table 1. Depicts a selection of software available from the Geomagic application suite, and corresponding open-source applications

Geomagic software	Description	Open-source alternative
Geomagic Capture	Scanner specific registration software	
Geomagic Design X	Rebuild CAD data reverse engineered from scans	OpenCAD
Geomagic Control X	Visualising and analysing data for quality control	Volume Graphics
Geomagic Freeform	Manipulate and manage large unstructured meshes	MeshLab

3.1.1 3D scanning software for 3D scanners

To process the results of the scanning process, various specialized software solutions are employed to manage scan data and enhance scenes. For this type of 3D scanning software, it's often bundled with 3D scanning hardware, and many developers have created their own software packages to accompany their laser scanners. Faro utilizes Faro Scene for scan registration and cleanup of collected geometry data, whilst Faro Zone 3D is used for tasks like importing high-res photos, utilizing registration targets, and performing metrics calculations within 3D reconstructions (Wang et al., 2019). Creaform's VX Elements is used to calibrate data collected from structured light scanners, while VX Model serves for more detailed scene modeling or measurements. Artec offers a comprehensive set of tools within Artec Studio, tailored for scan reconstruction and will be suitable for processing scan data. Additionally, CloudCompare (Open source) is an open-source solution that allows us to compare and edit point clouds or meshes (Dewez et al., 2016). It provides the capability to transform scan data to ensure alignment with our photogrammetry reconstructions.

3.1.2 Photogrammetry software

RealityCapture is renowned as one of the top choices for photogrammetric reconstruction for speed, accuracy, and format compatibility. Due to its exceptional capabilities, it is available at a premium price point. Other popular premium software includes Metashape (Agisoft) and Recap Pro (Autodesk).

There are many free photogrammetry software, the most popular of which includes Meshroom (AliceVision) which has been integrated as a free plug-in for 3D processing software such as Houdini (SideFX) and Maya (Autodesk). Other open source solutions include 3DF Zephyr, Colmap, and Regard3D.

3.1.3 3D mesh processing/modelling

3D mesh processing is a fundamental component of the 3D scanning and modeling pipeline, used to manipulate, refine, and optimize the three-dimensional mesh models generated from various data acquisition methods, such as laser scanning and photogrammetry. Most have access to various plug-ins which augment and enhance the capabilities of the software, unlocking a multitude of functionalities that cater to diverse project requirements.

Premium solutions include 3DS Max, Maya (both Autodesk), Houdini (SideFX), and ZBrush. Zbrush is well known in the professional industry for its many highly advanced tools for tasks like cleaning, healing, and texturing. 3DS Max offers cloth, light and liquid simulations and its own scripting language (MAXScript). Houdini’s procedural modeling solutions may provide scalability of modular components, enhancing the flexibility and efficiency of the asset creation and simulation process.

Blender is a remarkable free and open-source 3D modeling software known for its exceptional versatility. It offers a wide spectrum of capabilities, making it a powerful tool for cleaning up scans and repairing meshes. While Blender has a learning curve, due to its wide availability, there is a wealth of learning resources online for techniques such as hard surface modelling. There are also plug-ins which allow you to create highly detailed materials, like Substance Designer (Adobe), or create powerful renders of 3D objects. For tasks like modelling switchgear equipment, Blender’s extensive features make it an ideal choice for this purpose.

Among other open-source solutions are weaker options such as Autodesk TinkerCAD and Vectary. These free tools operate directly in your web browser, however, are primarily designed to educate entry-level users. For instance, TinkerCAD is often integrated into 3D printing processes and has limitations, such as restricting OBJ uploads to models with up to 300,000 faces.

More open-source options include OpenSCAD, FreeCAD, and Sculptris: OpenSCAD requires a bit of previous skill as you have to code your objects and it works with primitive geometric shapes and reads the code to modify and render them creating 3D models a with constructive solid geometry (CSG) which can be beneficial when it comes to 3D printing your projects. FreeCAD is a 3D modeling software was based on Python language which allows you to add new specialized features. Similarly Sculptris modifies pre-existing shapes with brushes of different strokes.

3.1.4 Games Engines

Lastly, the software we must consider is running the simulation so that it may be viewed and interacted with by a VR user. Unreal Engine 5 (Epic Games) natively supports VR development and also has the Quixel Bridge feature, giving easy access to tools and resources which may be beneficial or time saving for to the project, saving development labour. Similar plug-ins are available for Unity and the open-source Godot Engine. These games engines provide the necessary framework for creating immersive and interactive virtual environments based on the 3D models and assets generated during the scanning and modeling process.

3.2 Hardware

Hardware plays a significant role in capturing visual data and running the software necessary for asset visualization. To achieve accurate photogrammetric reconstruction, the quality of the captured images is essential, motivating us to explore several camera options, including the Mattterport Pro, DSLR cameras, and due to their wide availability we will also consider mobile phone cameras. For highly accurate metrology of our scanning targets, we shall review Lidar and structured light scanners. Lastly, we will address hardware that may be used to provide user interaction within a virtual environment, such as head mounted displays (HMDs) and review processing requirements.

3.2.1 Cameras and registration

Standard photographic equipment is often more accessible and cost-effective compared to other 3D scanning methods like LiDAR or structured light scanning. The camera will be used to gather input images to create a 3D model from photogrammetry with an accompanying texture. When aiming for the greatest accuracy, images with a higher resolution are preferred, therefore, to opt for a camera of superior quality is justified.

Various cameras may differ in quality, varying in number of pixels, sensor size, and field of view. Many pixels help to boost the image resolution to capture fine detail, most noticeable when zoomed in. Different lenses can be used with different DSLRs to correctly calibrate the cameras for scanning purposes. Conversely, smartphones may not have as many customisable options or similar fine-controls over the image capturing process, however as can be inferred from table 2, smartphones can often offer sufficiently high-quality visual data, as well as being widely available, highly portable and very accessible. Some smartphones have a single camera, others have dual sensors, quad sensors, however, frequently, high-megapixel cameras being used on market smartphones don't output photos as high as the camera is capable of because of pixel-binning.

Using a camera will be essential to capture texture and colour detail, as well as for providing proper reference for registration within the 3D processing software.

Table 2. Comparing the Megapixel value of various available camera devices.

Device		**Megapixels**
Mobile Phone	iPhone 14 Pro Max	48MP
		12MP
		12MP
	iPhone 11	12MP
		12MP
	iPhone 6	8MP
	Samsung Galaxy Fold 5G	16MP
	Google Pixel 7	50MP
DSLR Camera	Nikon D3300	24MP
	Cannon EOS ID Mark III	2.11MP
	Sony X7R	61MP

3.2.2 LiDAR Scanners

Table 3. Illustrating the range in available LiDAR scanners depending on the required range of the scan.

Manufacturer	**Short range**		**Medium Range**			**Long Range**	
Artec	Micro	Space Spider	Eva Lite	Eva	Leo	Ray II	
Faro	Gage FaroArm		Freestyle		Vantage	Focus	
Creaform	R-series		Go!Scan	HandyScan	MetraScan	MaxSHOT 3D	
Sick			S300 series			Tim-S	OutdoorScan 3
Leica					BLK 360	RTC 360	Scanstation

LiDAR scanners are known for their high accuracy and ability to capture intricate details. For the purposes of this project, they will be used for capturing complex geometries and surfaces with varying textures. Different scanners with different features are better suited to various scanning tasks depending on the object size and the necessary scan quality. Faro are well known for their mid-long-range scanners, and Creaform have also been used for their handheld scanners by similar project. Other scanners include the Geomagic capture and capture mini, ideal for "desktop scanning" of small objects up to the size of a shoebox, as well as the EinScan product range from Shining3D.

Certain scanners integrate both camera components and structured-light sensors. This grants the scanners the ability to gather supplementary colour information, which is particularly valuable for laser position-tracking and registration processes. Some artec scanners include cameras, allowing colours that the texture camera has captured to the 3D mesh being created. The quality of this texture is sufficient for a majority of metronomic applications. The quality depends of the generated geometry depends on the selection of the scanner, on the scanning distance, the lighting conditions, and the general execution of the scanning routine.

3.2.3 Matterport

Matterport is a company specializing in 3D scanning technology and software to capture and render 3D models of physical spaces. Their Matterport Pro Camera utilizes depth-sensing cameras and imaging sensors to create 3D point clouds of environments. The Matterport Pro2 3D camera offers 36MP images with a scan accuracy of +/- 50mm, while the Pro3 improves accuracy to +/- 20mm at a 10m distance. This tripod-mounted device captures comprehensive visual data by rotating 360 degrees in a short time. However, there are privacy concerns regarding detailed models unintentionally capturing sensitive information.

Matterport provides an iPad app for camera control, offering a "Dollhouse" view to identify unscanned areas. Users can navigate 3D models by selecting points within the model, making it popular for virtual property or office tours. They also have a mobile application using LiDAR sensors in phones to scan objects and generate 3D meshes in .obj format. While convenient, these scans may lack the precision needed for high-fidelity virtual assets, particularly in capturing intricate surface details.

For this project, Matterport services have drawbacks. They can be costly due to hardware expenses, service charges, and the need for additional payment to access the metadata folder (MatterPak). The generated point cloud format (.xyz) lacks widespread compatibility, often requiring conversion to more universally accepted formats like .e57. Furthermore, Matterport's scanning technology might not provide the required accuracy and detail for the project, especially in capturing nuanced surface features necessary for high-fidelity 3D models.

3.2.4 VR Hardware

Different head-mounted displays have been designed for slightly different purposes. While most headsets come with controllers, not all controllers are the same. Because the head-mounted display is the hardware through which the student interfaces with the training environment, the controller will dictate the possible depth of interaction In the context of this research, the emphasis is on a cost-effective and immersive VR solution. Many VR headsets can run the proposed simulation. However, a mid-range specification HMD with stand-alone capabilities is preferred over more powerful and expensive headsets such as the HTC Vive Pro line of HMDs. This choice imposes certain technological limitations on the performance of the 3D virtual representation.

For this project, the target headset will be a Meta Quest 2 VR headset. As well as its performance capabilities, the oculus link cable accessory allows the HMD to interface easily with a PC for development and testing purposes. The Pico Neo line of HMDs boasts similar specifications as the Meta Quest 2, both headsets have previously been used for virtual training and education purposes (Cowie & Alizadeh, 2022; Han et al., 2022; Moolman et al., 2022).

4. EXEMPLIFYING THE FRAMEWORK: HIGH-VOLTAGE ELECTRICAL SWITCHGEAR

Photogrammetry excels in capturing high-detail visual information, although as mentioned the resulting three-dimensional information may be susceptible to gaps, noise and inaccuracies. To use a fixed-camera or a multicamera set-up is feasible only for objects compatible with the rig in scale and shape, meaning they are mostly applicable only for small-to-medium objects. We shall be capturing objects on the site of their professional environment, therefore lighting conditions may not be perfect. Because of this the geometry that will result from our photogrammetry effort will likely have inconsistencies and not be very robust. For this reason we shall not rely on geometry data obtained this way, however, efforts will be made to retain any worthwhile texture information generated by the photoscan.

The 3D geometry obtained from LiDAR scan will likely be more robust however due to poor exercise of control over the lighting conditions, a complete and consistent scan cannot be guaranteed. As mentioned in section 2, we shall seek to mitigate these inconsistencies by employing the light-section method and performing multiple overlapping scans. To avoid incongruities caused by erroneous position tracking, a consequence of featureless scanning geometry, one solution emerged as notably effective: affixing ping pong balls or golf balls onto the surfaces of the equipment using blue tack. This addition of texture intricacies facilitated a more precise registration of the scanner's position during the scanning process. As the scanner traversed the modified surfaces, the intricate texture details provided the necessary points of reference for the algorithms to accurately determine the scanner's movement. Consequently, the scanner's accuracy improved significantly, and the issues of slippage and positional loss were effectively mitigated.

After combining the LiDAR and photogrammetry data into a unified 3D visualization, we suggest employing Blender to refine and optimize this asset. In case the resulting asset falls short of the realism required for real-time VR, the reconstructed data will serve as a reference template for generating a new mesh. By utilizing the scan data as a guide, the precise measurements obtained from the scan data can inform the development of an equally accurate 3D object. Furthermore, we have access to suitable replacement textures to maintain our goal of photorealism. While this process may demand additional time and effort, it is essential for achieving an immersive virtual reality experience.

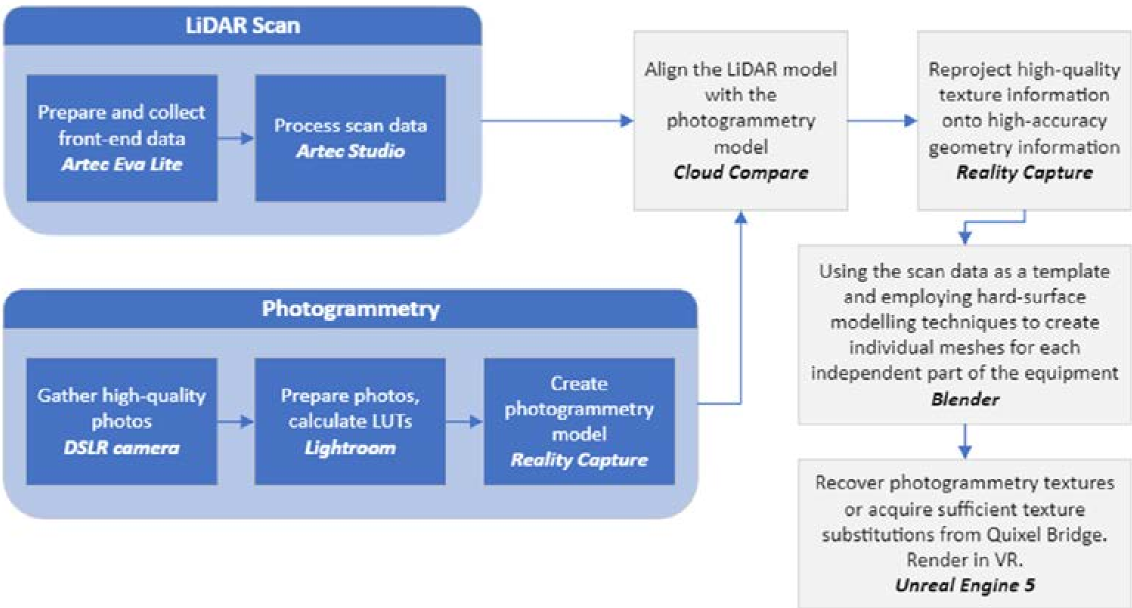

Fig 6:. Shows a process diagram outlining the methodology best suited to meet our needs of reconstructing a piece of equipment for virtual representation

5. CONCLUSION

This paper is structured to detail the methodological approach used in each stage, its limitations, and to empirically evaluate its effectiveness. By integrating advanced technologies and methodologies, this research strives to simplify the development of immersive training environments by reviewing and optimising the process of virtual representation. The framework presented is designed to methodically overcome various challenges, highlighting opportunities for automation of repetitious tasks associated with the necessary data processing, and facilitating a smooth shift from physical equipment to the production of highly lifelike virtual training environments.

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EVALUATION OF IMMERSIVE VR EXPERIENCES FOR SAFETY TRAINING OF CONSTRUCTION WORKERS: A SEMI-QUALITATIVE APPROACH PROPOSAL

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ABSTRACT: *The diffusion of Building Information Modeling (BIM) and advanced visualization technologies in the increasingly digitalised construction sector is fostering the development and implementation of disruptive approaches for workforce Health and Safety (H&S) training. Project-specific risks, safety procedures and information can be administered through immersive Virtual Reality (VR) experiences where construction site environments and activities are reproduced without exposing the trainees to real hazards. However, despite numerous research and industry applications demonstrating the potential benefits of these technologies, a standardized framework and methodology for the evaluation of VR safety training effectiveness for construction workers is still lacking hence hindering its large scale-adoption and recognition from policymakers. Within the scope of previous authors contributions on the development and implementation of BIM-based VR experiences for construction workers' safety training, this paper aims to address the evaluation of their effectiveness proposing a novel semi-qualitative approach based on the integration of trainees' subjective and objective data. A post-experience evaluation questionnaire is developed to collect trainees' direct and qualitative feedback about the experience immersivity and perceived safety content transfer. Furthermore, the integration with trainees' spatial tracking data is proposed to complement the qualitative feedback with the quantitative evaluation of their use of the virtual space for safety training purposes. The application of the presented approach in case study is currently undergoing and the related results will be subject of future contributions.*

Keywords: *Virtual Reality (VR), Construction worker, Safety training, Evaluation, Spatial tracking, Heatmap visualization, Survey*

1. INTRODUCTION

Despite recent technological innovations and policy improvements in workforce Health and Safety (HS) are contributing to a low but steady reduction in accident rates, the construction industry is still one of the most dangerous, accounting for one fifth of yearly workplace fatal accidents in the European Union alone (Eurostat, 2022). In this regard, the growing adoption of real-scale immersive visualizations of complex site scenarios and construction activities enabled by Building Information Modelling (BIM) and Virtual Reality (VR) technologies are supporting HS managers in the early identification and mitigation of safety risks (Babalola et al., 2023). Moreover, since their early applications, it has been acknowledged that immersive VR simulations of project-specific site layouts and activities can improve the transfer of safety contents and preventive procedures to the trainees, while empowering their awareness in later real-site hazardous contexts (Rokooei et al., 2023). However, the administration of VR experiences for construction workers safety training is far from substituting traditional methods (e.g., slides) and is still confined to a minor share of early adopters. In fact, while economic and technical barriers have progressively shrunk, the lack of standardized frameworks and methods for the evaluation of the effectiveness of construction site VR training still stands as a major obstacle for its recognition from policy makers

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Vito Getuli, Valentina Fornasari, Alessandro Bruttini, Tommaso Sorbi, Pietro Capone, *Evaluation of Immersive VR Experiences for Safety Training of Construction Workers: A Semi-Qualitative Approach Proposal*, pp. 288-297, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.27

and hence for their large-scale adoption in the industry. In this context, several contributions have shown how the quantification of the trainee's ability to perform cognitive and practical tasks in the VR environment (e.g., hazard identification, activity simulation) can be used to objectively assess the training effectiveness (Li et al., 2018). Nonetheless, the qualitative evaluation of VR training, collected via post-experience questionnaires administered to the trainees, is often overlooked or tailored on a specific application, so that its reuse in other case studies is impractical.

To address the mentioned open issues in the evaluation of VR safety training experiences for construction workers, this paper proposes a novel approach based on the integration of trainee's subjective perception and objective VR spatial usage. The former is collected through a questionnaire administered to the trainee after the experience and divided in five inquiry areas. For the latter, the acquisition of the users' spatial track during the VR experience and its restitution in a BIM environment through an heatmap visualization is proposed to evaluate the trainees' use and understanding of the virtual environment in relation to safety training purposes. The present work stems from previous authors' contributions in the development and administration of BIM-based immersive VR site simulations to construction workers for HS training and management purposes and is currently being tested in an infrastructure project case study whose results will be subject of future contributions (Getuli, Capone, Bruttini, & Sorbi, 2020; Getuli et al., 2018, 2021, 2022).

2. BACKGROUND

The use of virtual reality as a safety training technology is gaining attention in the construction industry. While many of the current studies mainly focus on the development of VR-based safety training programmes, it is noticeable that there is still a lack of research focusing on assessing its effectiveness. In this section, an overview of the state of the art with regard to the use of immersive virtual reality used in the realisation of training sessions for workers is given and, finally, the identified open problems and obstacles to implementation that this research aims to address are reported.

2.1. BIM and Virtual Reality for construction workers' safety training

Increasing use of BIM is favouring the adoption of VR in the Archtiecture, Engineering and Construction (AEC) sector. Typical applications for VR include construction safety planning and training (Azhar, 2017), production planning and design review sessions (Wolfartsberger, 2019).

In recent years, several studies have shown that BIM models can be used to represent construction site layouts and extract data for space and activity optimisation (Tao et al., 2022) and apply automated safety rule checking to simplify hazard recognition and assessment and risk assessment activities (I. Kim et al., 2020). Most of all, the spatial understanding and information visualisation capabilities provided by construction site BIM models have been harnessed to transfer general and project-specific HS knowledge with the implementation of VR technologies for the reproduction of construction site scenarios and activities for worker safety training and site planning (Getuli & Capone, 2018).

Several studies investigated the use of virtual reality to allow construction workers and supervisors to have easy access to the BIM through a simple VR interface and also for the education of students, defining an efficient educational tool by integrating VR application and BIM model information to develop 3D, 4D, and 5D simulations (Esfahani, 2023) and offering suggestions to AEC educators and students in implementing BIM-into-VR in different courses.

The use of virtual reality as a safety training technology is gaining attention in many different fieds: using a fully immersive VR has been shown to offer numerous benefits in terms of the effectiveness of health and safety training including risk assessment, machinery and/or process operation training in various industries (Toyoda et al., 2022).

VR is gaining attention also in the construction industry, but while many of the current studies mainly focus on the development of VR-based safety training programmes, it is noticeable that there is still a lack of research focusing on improving its effectiveness. It has been shown that telepresence experienced through VR and learners' perception of the risk of occupational accidents significantly influence their satisfaction with VR-based safety training, thus influencing its effectiveness (Yoo et al., 2023).

2.2. Construction workers' safety training evaluation

The evaluation of the effectiveness of simulations developed in VR during the training sessions or the validation of the experience carried out is a key step to identify different problems and to be able to solve certain situations by fully improving the training activity for trainees, but while VR-based training has been proven to improve learning effectiveness over conventional methods, there is a lack of study on its learning effectiveness due to the implementation of training modes. It is known that BIM and VR for safety training of construction workers are useful in many contexts (Afzal & Shafiq, 2021), although there is still no standardized method to evaluate the effectiveness of safety content transfer. In fact, most of the proposed methods are specific to individual case studies or applications in different fields, and the effectiveness of the training administered as perceived by the trainee and the spatial understanding of the worksite scenario and activity in VR is often overlooked.

The evaluation of the user experience in virtual environments can be done either with subjective methods, such us questionnaires (H. K. Kim et al., 2018) or with objective methods, like eye-tracking, or brain activity measurements (Hertweck et al., 2019).

Regarding to the evaluation of the VR safety training of construction workers, several survey methods were proposed, including the creation of a questionnaire containing open and closed questions to evaluate various aspects of the VR interface on a scale of 1 (poor) to 5 (excellent) with subsequent collection of further data through observations and conversations with participants during and after the VR tests (Johansson & Roupé, 2019). Questionnaires are a widely used and well-known tool to collect user feedback and changes in mental states during various activities (Robinson, 2018) including VR applications.

Although the use of objective measurement methods is promising, questionnaires are the most frequently used tool in user experience studies for VR. These questionnaires can be used as pre-, real-time, or post-assessment methods. In pre-surveys, the user is not immersed in a virtual environment: this can lead to a less dominant difference between VR and the traditional desktop presentation of questionnaires. After immersion into the virtual environment, however, it is important to investigate the influence of the type of questionnaire presentation on user experience (Safikhani et al., 2021).

Another important topic is the movement or spatial tracking of workers during VR simulation of construction activities, that has been shown to be useful for ergonomic evaluation of workstations or assembly procedures (Getuli, Capone, Bruttini, & Isaac, 2020).

Some studies demonstrate the effectiveness of VR simulations of assembly lines and task scenarios in an ergonomic approach to workplace design, aimed to optimize the production and the human-machine interaction (Caputo et al., 2018). Through the collection and analysis of the position tracking of a worker (Michalos et al., 2018) and human motion and posture tracking systems is possible to obtain reliable and repeatable measures to be used for evaluation of activity and workplace-related working postures.

2.3. Open issues

Although BIM and VR for construction workers' safety training has been proven beneficial in many studies, there is still a lack of a standardized method to evaluate safety contents transfer effectiveness. Most methods are specific to single case studies or applications; they are used to assess the training on objective quantification of the trainee ability to accomplish tasks in the VR environment but overlook trainee's perceived effectiveness of the administered training and spatial understanding of the construction site scenario and activity in the VR, and ignore the subjective worker perception.

Movement or spatial tracking of the trainees/workers during VR simulation of working activities has been proven beneficial for the ergonomic assessment of workstation or assembly procedures but not yet to evaluate the spatial understanding of the trainee in VR safety training experience that could instead be leveraged in the safety content transfer evaluation of HS training VR experience.

3. PROPOSED APPROACH

The aim of this paper is to propose an evaluation method of VR safety training experiences for construction workers that is based on the integration of a qualitative survey of the experience and spatial tracking data of participants. To this end, first a dedicated questionnaire was developed to evaluate both the immersiveness of VR experiences and the effectiveness of the safety content presented. Then a study on the benefits of tracking and visualizing trainees' use of space in the virtual environment is proposed. Finally, the proposed approach was validated within a case study previously developed by the authors and used for BIM-based construction worker safety training in VR.

As mentioned above, the proposed approach is based on the integration of two main categories of data, as illustrated in Figure 1. The overall goal is to collect a set of data from trainees experiencing immersive VR training, aimed at evaluating the effectiveness of the virtual experience. The detailed description of the types of data to be collected and the specific purpose for which they need to be obtained then follows in Sections 3.1 - 3.2.

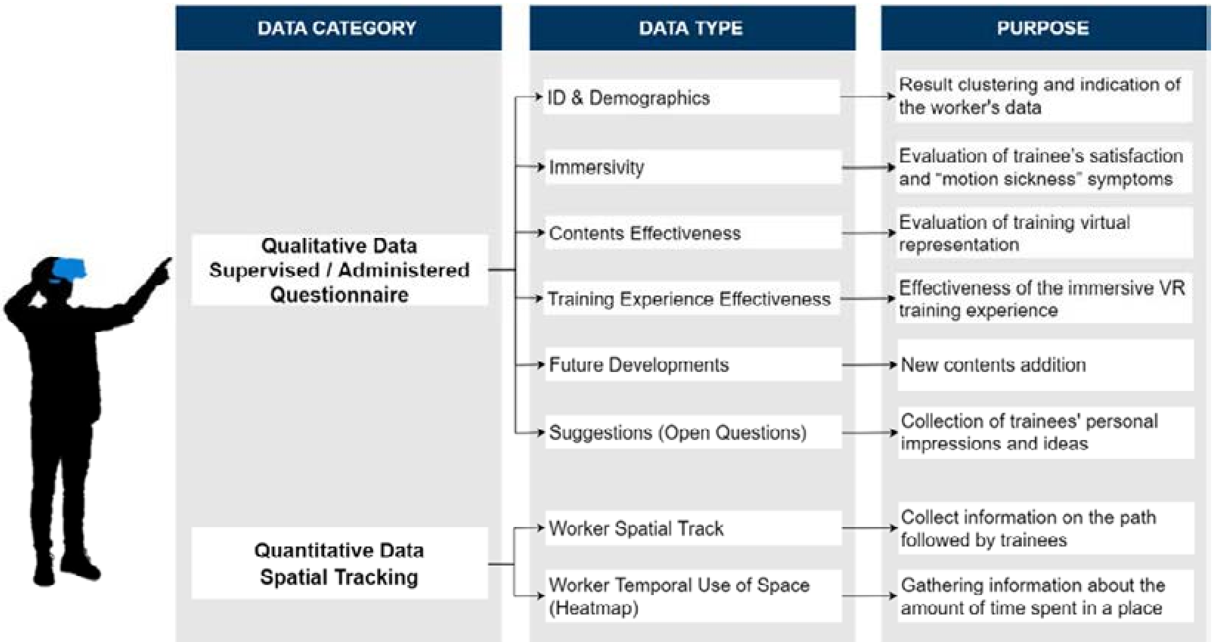

Fig. 1: VR safety training experience effectiveness evaluation approach – Data schema

3.1. Post-experience evaluation questionnaire

The approach adopted for the creation of the evaluation questionnaire led to the distinction of two main sections: the first section includes the trainee's personal data, while the second section corresponds to the actual evaluation part. The latter includes both a series of evaluation questions, for each of which the trainee can give a score on an increasing scale from one to five (where five represents maximum satisfaction), and an open "suggestions" section to collect trainees' personal impressions and ideas. Table 1 shows the sections and subsections with an indication of the purpose for which it was deemed necessary to include them, a brief description, and an explanatory example.

3.2. Trainee's spatial tracking and use of space visualization

From the immersive VR experience, data are collected not only directly, by filling out questionnaires, but also indirectly with the acquisition of the worker's position in the virtual environment. The latter procedure involves capturing the position of the worker in the VR environment during the entire course of the simulation in order to analyse the actual use of the workspace and is recorded with a data acquisition rate of 1 Hz. The 3D point sequence resulting from this process is then converted for the generation of heatmaps within which the position of the worker is represented with a gradient of colour ranging from green to purple.

As with the formulation of the questionnaire, mentioned in the previous paragraphs, an approach was defined to analyse worker movement during the immersive VR experience in order to visualize position tracking. This methodology involves taking into account not only the spatial coordinates, but also the time duration required for the performance of the experience.

Table 1: Questionnaire contents

Data type	Description	Example
ID & demographics	The worker's data, which includes an identification code/number (ID) for classification of the completed questionnaire and an indication of the worker's age, role/occupation and company, with the purpose of clustering the results obtained. [Text]	ID (Number) Age; Company; Role
Immersivity	Questions related to the user's ability to get immersed in the virtual experience, useful for assessing how engaged the trainee actually was in the virtual training scenario. It consists of an assessment of the trainee's satisfaction in terms of both ease of use and comfort (also related to the possible onset of symptoms of "motion sickness"). [Single rating – Likert scale]	How much did you like the experience? [min 1; max 5]
Contents' effectiveness	Questions regarding the virtual representation of the site and security content, aimed at evaluating the effectiveness of the experience against the objectives of the training session. [Single rating – Likert scale]	How accurately does the virtual construction site reproduce the real one? [min 1; max 5]
Training experience's effectiveness	Questions pertaining to the overall effectiveness of the experience, aimed at investigating the actual usefulness of the immersive VR training session and whether it turns out to be as comprehensive and exhaustive as a traditional training session. [Single rating – Likert scale]	Do you think this experience is useful in understanding the hazards present on the construction site? [min 1; max 5]
Future development	Questions concerning the introduction of new automation or virtual content aimed at enhancing the immersive VR training experience through the inclusion of even virtual objects with enhanced interactivity. [Single rating – Likert scale]	Would you like to be able to grasp and use objects from the construction site? [min 1; max 5]
Suggestions	Open question to collect personal impressions and ideas from the trainees. [Text]	Suggestions

Table 2: Heatmap schema contents

Data type	Description	Example
ID & demographics	See Table 1	See Table 1
Training experience duration	The duration of the experience from start to finish, excluding the tutorial that is run at the end to explain the operation to trainees, takes into account how long it takes the user to complete the experience. [time in seconds]	523 sec
Worker spatio-temporal track	The graphical representation is given by a series of points that correspond to the coordinates of where the user was every 1 second and are used to create an image that shows the path followed by the worker distinguished with different colours. [Frequency in Hz]	Image with coloured representation of the worker's followed path. [min. green, max. purple]

4. IMPLEMENTATION

The area in which this paper is located is part of a previous research project in which the authors' goal was to develop a prototype protocol for the design and delivery of safety training to construction workers, based on an innovative and interactive learner-centred approach. This protocol was designed and then tested for validation in a construction project in Italy that served as a case study for the development of VR training session content and implementation (Getuli et al., 2021). During and after the exploration of the site phases implemented, the worker undergoing the experience was invited to provide indications and opinions regarding the work environment in which he/she was working. This was done with the aim of both validating the different site layouts designed and to collect any objections and/or observations from the worker, thus enhancing their experience and giving it due importance within the development process of the virtual reality training experiences covered by this research work.

In order to collect direct feedbacks and suggestions to better drive the decision of the development direction of the implementation of the proposed VR training protocol, an evaluation questionnaire (Fig.4) was administered from a staff member to every trainee involved after they finished their test training session. The authors drawn the questions in relation to the following development areas, weighting the number of the questions for each one according to their research objectives:

- **Immersivity**: (question 1 to 4) Evaluation of the trainee's satisfaction in terms of ease of use and comfort (also related to eventual "motion sickness" symptoms occurrence).
- **Contents' effectiveness**: (question 5 to 10) Evaluation of the site's and the safety contents' virtual representation in respect of the purposes of the training session.
- **Training experience's effectiveness**: (question 11 to 14) Evaluation of the overall effectiveness of the immersive VR training experience.
- **Future development**: (question 15 and 16) Evaluation of the introduction of audio and enhanced object's interactivity as new features to be implemented in future developments.

For each evaluation question the trainee can give a score on an upward scale from one to five, where five represents the highest satisfaction. Furthermore, an open "suggestions" section is added to collect personal impressions and ideas from the trainees. All the results were collected and processed in anonymous form.

User Data	
ID:	
Age:	
Company:	
Role/Job:	

	Questionnaire	min - max
Immersivity	1) Did you enjoy the experience?	1 2 3 4 5
	2) Were you comfortable during the experience?	1 2 3 4 5
	3) Was it easy to use the viewer and controller?	1 2 3 4 5
	4) Did it bother you not being able to see your body in the virtual world?	1 2 3 4 5
Contents' Effectiveness	5) Are the signal arrows helpful in figuring out where to go?	1 2 3 4 5
	6) Does the virtual construction site sufficiently replicate the real one?	1 2 3 4 5
	7) Do the work spaces indicated for the work seem adequate?	1 2 3 4 5
	8) Are the safety and hazard spaces useful in signaling hazardous areas?	1 2 3 4 5
	9) In your experience, are the work procedures reproduced correct?	1 2 3 4 5
	10) Do you think this experience is useful in getting to know the worksite before entering it?	1 2 3 4 5
Training Experience's Effectiveness	11) Do you think this eperience is useful in understanding the hazards present at the worksite?	1 2 3 4 5
	12) Is this type of training useful for an inexperienced worker?	1 2 3 4 5
	13) Is this type of training useful for an experienced worker?	1 2 3 4 5
	14) Would you prefer to see people and machines in motion ?	1 2 3 4 5
Future Development	15) Would you prefer to hear sounds and noises inside the worksite?	1 2 3 4 5
	16) Would you like to be able to grasp and use worksite objects?	1 2 3 4 5

Suggestions

Fig. 2: Scheme of the VR training session evaluation questionnaire administered to the trainees

In addition to the data collected in active form through the questionnaires, an algorithm for recording the position of the worker in the virtual reproduction of the worksite was integrated into the VR training experience applications. In this way, during the training experience, with an acquisition frequency of 1 time per second (1 Hz), the coordinates of the worker's position are recorded in relation to both the work spaces designed for the simulated construction activities, and in general in his movement within the construction site, so that his aptitude for recognising risk areas can be assessed a posteriori at both the site and activity scales.

The interpretation of the movement traces acquired by the VR device during training in the form of sequences of points in the virtual space of the worksite was conducted by developing an additional analysis algorithm capable of reporting this information within the BIM model of the worksite and providing a graphic interpretation by means of heat-map visualisations. These visualisations allow the temporal dimension of the path followed by the worker in VR to be reported in a planimetric elaboration, distinguishing with different colours, in accordance with a pre-set gradient, the areas where the worker spent the longest time (violet, red) from those of short passage (green).

The tracking of the worker's position recorded during the VR activity simulation is done by visualizing the worker's use of space based on a temporal heat map, which consists of a 2D representation of the 3D position points recorded by the worker. The time dimension of the position tracked by the worker is graphically represented through a colour gradient (green to red), so that a red-coloured area represents a previously recorded position (red indicates a position occupied longer during the VR simulation). The heat map is then automatically generated using a custom algorithm specially developed by the authors.

Comparison of the generated heat map with the initial configuration of the workspace, in a BIM modeling environment, allows for early identification of possible planning errors; in fact, the results of the analysis of the obtained data are necessary for the next planning step, i.e., modification of the workspace configuration.

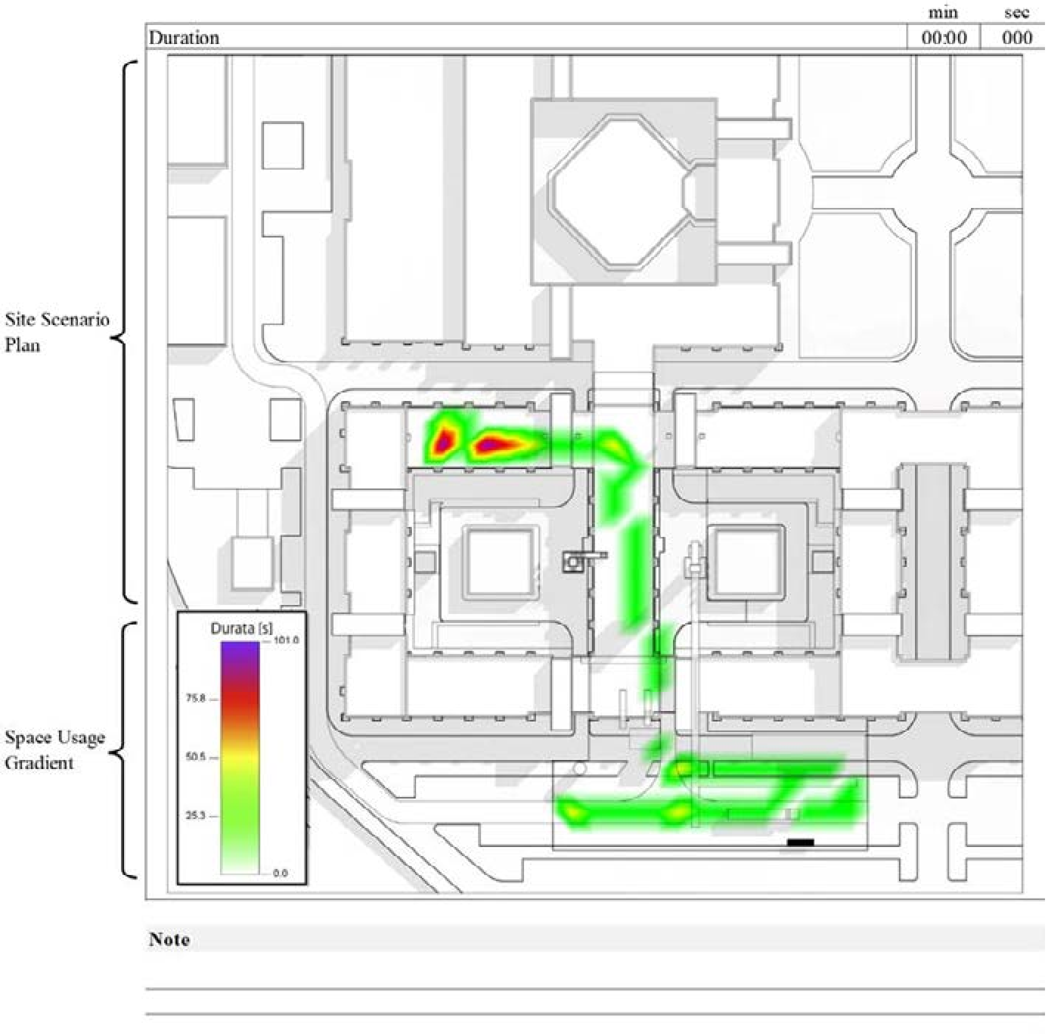

Fig. 3: Heatmap visualization (plan view) of the trainee usage of the virtual training environment

5. CONCLUSIONS

The present work, through implementation of an approach based on the integration of two main categories of data, with the overall objective of collecting a set of data from trainees experiencing immersive VR training to evaluate the effectiveness of the virtual experience, contributes to the development of a standardized method of evaluating the effectiveness of safety content transfer to workers that does not neglect the trainee's perceived effectiveness of the administered training and spatial understanding of the worksite scenario and activity in VR, as is the case with most of the methods proposed in the literature that are specific to individual case studies or applications and evaluate training based on an objective quantification of the trainee's ability to perform tasks in the VR environment.

The developed questionnaire, dedicated to evaluating both the immersiveness of VR experiences and the effectiveness of the safety content presented, and the proposed study on the benefits of tracking and visualization of learners' use of space in the virtual environment, allowed us to conduct an evaluation of safety training experiences in VR for construction workers, based on the integration of both a qualitative survey of the experience and the participants' spatial tracking data. Spatial tracking of trainees and their movement in space during the VR simulation of work activities proved useful for the evaluation of trainees' spatial understanding of the VR safety training experience.

Finally, the proposed approach was validated within a case study previously developed by the authors in which the authors' goal was to draft a prototype protocol for the design and delivery of safety training to construction workers, based on an innovative and interactive learner-centred approach. That protocol was designed and then tested for validation in a construction project in Italy that served as a case study for the development of BIM-based construction worker safety training in VR. During that work, a total of 6 VR training experiences were developed for workers, the contents of which consisted of the 3D models needed to reproduce the construction site scenario of the case study in the first 3 phases of construction: site set-up, installation of the external staircase and erection of the tower crane. At the same time, 4 training days were organized, during which the results of the proposed questionnaires were collected with reference to the different VR experiences carried out.

During and at the end of each VR training session of the 6 different site phases implemented, the worker undergoing the experience was asked to fill out the questionnaire developed to provide input and opinions on the work environment they were in, for the evaluation of the session, in order to enhance the experience and collect useful data for the development of subsequent implementations. The results obtained from the above evaluation and the discussion of the related case study previously mentioned will be the subject of further publication.

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ENHANCING COLLABORATION WITH BLOCKCHAIN-ENABLED DIGITAL TWINS: PERSPECTIVES FROM STAKEHOLDERS IN THE BUILT ENVIRONMENT

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ABSTRACT: *This study explores the potential of Blockchain (BC)-enabled Digital Twins (DT) using qualitative semi-structured interviews to investigate the perception of stakeholders in the Architectural, Engineering, Construction and Facility Management (AEC-FM) industry on the relevance of BC-enabled DTs in augmenting stakeholder collaboration. The findings revealed that most interviewees perceived the potential of a BC-enabled DT in fostering stakeholder collaboration, leading to enhanced project delivery. Some participants viewed affordability drivers, whilst some highlighted the desire to fulfil client demands as influencing drivers for BC-enabled DT implementation in the AEC-FM industry. The study's empirical findings align with evidence from other industrial sectors, proving that BC can ensure data integrity in a decentralised peer-to-peer framework, whilst DTs can leverage that data for effective and reliable decision-making. In the AEC-FM industry, these technologies are nascent; however, their potential integration could tackle critical issues regarding stakeholder collaboration and information fragmentation, leading to value generation in a decentralised and immutable manner. This study offers insights into implementation strategies for a BC-enabled DT collaborative environment and contributes to accelerating the industry's approach to digital transformation.*

KEYWORDS: *digital twins, blockchain, drivers, collaboration*

1. INTRODUCTION

In a project-dominant sector like the Architectural, Engineering, Construction and Facility Management (AEC-FM) industry, collaboration is seen as a critical catalyst in boosting efficiency, promoting information sharing, facilitating effective decision-making, and improving the quality of production processes and project-based performance (Koolwijk et al., 2018). Unfortunately, collaboration in the sector is beleaguered with mistrust, ineffective communication, adversarial relationships, and unnecessary disputes. This has resulted in the industry's fragmented nature and inconsistent activities by different participants, hindering progress towards project targets and creating a significant barrier to success (Li et al., 2021; Prebanić & Vukomanović, 2021).

Fragmentation of the AEC-FM industry is further compounded by the industry's complex activities due to the variety and volumes of entities involved (Chen et al., 2022), the duration of a project, the amounts of relevant data generated and dispersed stakeholders who work at the different phases of a built asset's lifecycle. Therefore, this creates breeding grounds for loss of crucial information, untracked implementation, and, most importantly, the failure to meet client requirements. Given the industry's complexities, it is essential to identify tools or solutions that can improve collaboration and contribute to process efficiency.

There has been an increasing trend in adopting digital technologies in various industries (Pour Rahimian et al., 2022), especially with the advent of Industry 4.0, to overcome industry complexities. However, the AEC-FM industry has slowly adopted, used, or applied emerging digital technologies (Newman et al., 2021). Studies show that applying digital technologies such as Building Information Modelling (BIM), Digital Twins (DT), Distributed Ledger Technologies (DLT) or Blockchain (BC), Internet of Things (IoT), and Augmented or Virtual Reality in the AEC-FM industry can increase productivity, collaboration, quality, and efficiency (Olanipekun & Sutrisna, 2021). Under the concept of Construction 4.0, the AEC-FM industry is making efforts to adopt such emerging technologies and utilise their advanced capabilities (Opoku et al., 2021).

BIM is now widely recognised as an effective way to facilitate collaboration, communication, and management. It is a common tool or process that provides a high level of information depth (Gan et al., 2019), containing all necessary details about objects and processes for the asset's entire lifecycle and the different stakeholders involved (Khajavi et al., 2019). Despite the well-known benefits of BIM in terms of collaboration, issues relating to collaboration persist (Oraee et al., 2021); these might stem from a lack of shared collaborative culture, limited understanding of emerging technologies among project teams, and a preference for traditional methods (Che Ibrahim et al., 2019; Ibrahim & Belayutham, 2019). Furthermore, the multi-level capabilities of BIM are limited to implementation without the inclusion of real-time information to achieve a close-to-"as-built" or "up-to-current"

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)

state of the built asset being actualised in physical form (Lu et al., 2021). Wang et al. (2020) suggest that the absence of real-time information exchange can lead to fragmented and discontinuous actions among participants. Therefore, a collaborative platform allowing real-time information sharing among all parties is necessary.

DT technology has immense potential to facilitate real-time communication and collaboration among project participants (Lee et al., 2021). DT surpasses BIM by providing more "up-to-current" modelling (Rao et al., 2022; Xie et al., 2020). Integrating IoT sensors and DTs can also transform BIM into a dynamic tool, automatically updating as-built BIM (Dudhee & Vukovic, 2021). Furthermore, DTs can simulate "what-if" scenarios with AI-based techniques to identify potential solutions to issues such as cost overruns and schedule delays, enabling stakeholders to make proactive decisions (Lee et al., 2021). In addition, DT technology offers a shared virtual environment where project participants can visualise the project, discuss options, and ultimately make well-informed decisions (Zhao et al., 2022). Several studies have emphasised that creating and managing DTs is a continuous process relevant throughout a built asset's lifecycle (Xie et al., 2023). However, these studies have also highlighted the importance of ensuring data security, reliability, and improved collaboration (Hellenborn et al., 2023).

BC technology is anticipated to fuel innovation in essential areas such as security, trust, and coordination with unified standards and protocols for information sharing. This decentralised, peer-to-peer framework is based on cryptographic mechanisms (Elghaish et al., 2022; Talla & McIlwaine, 2022) and could be an ideal solution to tackle the challenges of DT concerning security, reliability, and transparency (Kiu et al., 2022). BC enables a secure electronic ledger of digital information, utilising hash values to enhance security. BC uses consensus protocols through a decentralised network to ensure data reliability and encourages collaboration among project participants to record, verify, store, and extract construction project information and transactions without centralised data intermediaries (Kim et al., 2020).

When it comes to the digital transformation in the AEC-FM industry, the integration of BC and DT technology poses the potential to ensure data integrity, security, and trustworthiness, thereby enabling more effective collaboration among stakeholders (Adu-Amankwa et al., 2022); however, only limited studies on its potential integration can be found in AEC-FM literature. Additionally, its adoption and potential integration may be a complex phenomenon which could be influenced by factors considered from multiple perspectives. Hence, investigating and exploring stakeholders' perspectives on the potential of a BC-enabled DT collaborative approach can contribute to designing a framework and informing policymakers towards its successful adoption and implementation. To help contribute to the limited studies on BC-DT integration, this current study aims to explore and understand the perspectives of the industry's stakeholders on the potential applicability of BC-enabled DT collaborative approach using qualitative semi-structured interviews. In line with the aim, the study seeks answers to the following research questions:

- What do industry stakeholders perceive as the potential role(s) of BC-enabled DT collaborative approach?
- What factors would motivate industry stakeholders to pursue a BC-enabled DT approach to collaborative working?

The remainder of the article is structured as follows: Section 2 reviews relevant literature, while Section 3 explains the methodology used. Section 4 presents the results and discusses the perspectives of the study's participants. Finally, Section 5 summarises and concludes the study.

2. LITERATURE REVIEW

The impact of BC-enabled DT approach on collaboration is increasingly studied, particularly in the energy, health, manufacturing, and transportation sectors. For instance, studies by Huang et al. (2020) demonstrated the effectiveness of a data management platform for a turbine using a BC-based DT approach to help curb problems associated with data storage, data access, data sharing, data authenticity, and overwritten data. The results of their approach indicate the potential of BC-based DT to guarantee data storage, access to verified data, sharing efficiency via a peer-to-peer network, and data authenticity through traceability. In another study, EL Azzaoui et al. (2021) created a BC-based DT framework for a smart health city to ensure user identity is secure and data is anonymously available only to healthcare providers and professionals for real-time data analytics, research, and personalised treatment. The framework has the potential to enhance treatment accuracy, predict future diseases, and control them. The authors also suggest that in a COVID-19 scenario, this framework could be used as a collaborative approach to provide a secure, shared database where healthcare providers and professionals can access data anonymously and use that data to improve treatment and prevent future pandemics. In a recent study by Tao et al. (2022), a BC-based platform was proposed for better management of manufacturing services. The platform aims to improve trust among collaborators by ensuring accurate information sources and secure data. The authors explain that despite the challenges posed by the lack of interaction between physical and cyber spaces, the proposed platform offers a reliable solution for cyber-physical integration and addresses issues of distrust commonly associated with such service platforms.

In AEC-FM literature, Lee et al. (2021) developed and tested a BC-DT integrated framework to support accountable sharing of project-related information among stakeholders. According to the authors, integrating BC and DT can ensure authentic real-time construction-related data is traceable, immutable, and shared among project participants without an intermediary. Similarly, studies by Teisserenc and Sepasgozar (2022) posit that BC-enabled DT will allow real-time monitoring of assets whilst supporting data decentralisation and enhancing data traceability, security, and privacy. In another study, Jiang et al. (2022) suggested that a BC-enabled DT collaboration platform can establish a virtual space for real-time monitoring, decision-making, and communication among different parties in a project.

These studies demonstrate that integrating DT and BC can facilitate collaborative work practices by improving stakeholder communication, maintaining secure data integrity, and creating an authentic digital representation of the physical asset or process being twinned. In addition, these studies have management implications that can be useful for monitoring data in real time, exchanging data and information securely, and making trustworthy and transparent decisions. However, despite these studies, only a few have attempted to explore and understand its applicability in the context of the AEC-FM sector. Furthermore, there is a need to test these theoretical promises through empirical research, using both qualitative and quantitative methods to discover robust knowledge. This will help gain a more thorough understanding of their relevance within the AEC-FM industry and increase awareness about their potential benefits. Hence, seeking input from key stakeholders can offer valuable insights into the advantages of implementing a collaborative approach incorporating DT and BC technologies and the driving factors behind its adoption.

3. METHODOLOGY

A qualitative methodological approach focusing on conducting semi-structured interviews was mainly employed for this study. This approach was adopted due to its potential to gather comprehensive data and generate rich insights (Bryman, 2016). Hence, using this approach to explore and understand stakeholder perceptions about DT and BC technologies for the AEC-FM industry will enable participants to provide rich perspectives based on their knowledge and expertise. Through purposeful sampling, participants were sought through online networking websites (e.g., LinkedIn) and peer recommendations (Bryman, 2016). The main areas of interest were those participants with knowledge or experiences about DT, BC, or both in the AEC-FM industry. Nevertheless, flexibility was employed for some profiles which didn't express explicit expertise in those fields but were keen to participate in the study because of their broader knowledge of digital transformation in the AEC-FM sector.

3.1 Data Collection – Semi-structured Interviews

After ethical approval was granted to engage participants for data collection, potential candidates were approached for their consent to participate in this study. According to Saunders et al. (2019), a range of 5-25 participants is adequate for qualitative interviews. Thus, this study included 19 AEC-FM industry professionals and scholars from Asia, Europe, North America, and Africa.

The researchers employed a semi-structured interview protocol to organise detailed and orderly interviews, including open-ended questions to collect meaningful comments from respondents (Yin & Campbell, 2018). The interviews were conducted via web meetings on MS Teams to accommodate a wider reach of participants and allow effective capturing of responses for transcription. Accordingly, before each interview session, participants were briefed on the study's aims, any concerns were addressed, and their consent was formally sought to officially commence the interview process.

3.2 Data Analysis – Thematic Analysis

With the aid of NVivo, the transcribed responses from participants were progressed into the data processing and analysis, where available information within each response sheet was extracted into self-describing categories and held under thematic codes to identify the scope or variety of relevant constructs (Saldaña, 2021). Emerging themes highlighting the potential role of BC-enabled DT perceived by participants and the drivers or influential factors towards its adoption were identified. The emerging themes identified were guided by the study's focus, as suggested by Bryman (2016).

4. RESULTS AND DISCUSSION

4.1 Demography of Interviewees

A total of 19 participants hailing from Africa, Asia, Europe, and the Middle East were involved in this study. These participants were classified according to their field of expertise, which included Academics, Managers, Architects, Engineers, Programmers, and Surveyors.

4.2 Participants' Perspectives on the Role of Blockchain-enabled Digital Twins

During the interviews, individuals were asked to provide insights on a BC-enabled DT approach's role in collaborative working within the AEC-FM industry. Drawing from their extensive knowledge and understanding, they affirmed that a BC-enabled DT would be crucial for four main themed functions on effective collaboration, as it would provide a secure environment for accessing and sharing data, improve decision-making and promote trust and transparency (see Table 1).

Table 1: Summary of Themes about the Role of Blockchain-enabled Digital Twin from Participant

Theme	Descriptions	No of Participants
ENHANCED DATA ACCESSIBILITY	This theme comprises views on the role of blockchain-enabled digital twin in easing stakeholder access to data	9
DATA SECURITY	This theme comprises views on the features of blockchain-enabled digital twin in assuring the security of data	3
ENHANCED DECISION-MAKING	This theme highlights views on the role of blockchain-enabled digital twins in assisting with decision-making	3
TRUST AND TRANSPARENCY	This theme comprises views on the relevance of blockchain-enabled digital twins in ensuring trust and transparency	2

Regarding the popularity of themed responses, it is observed from Table 1 that most participants expressed sentiments about enhanced data accessibility, followed equally by data security, as well as enhanced decision-making, and finally, trust and transparency. Nevertheless, the number of participants is only an indication of interest as some participants may be represented across themes, so in this paper, the contents that comprise these themes are of interest. The subsequent subsections delve into the themes with supporting evidence quotes.

4.2.1 Enhanced Data Accessibility

Most of the interviewees revealed that opting for a BC-enabled DT solution will create a platform where data can be accessed easily by project participants and stakeholders. They expect that BC's added characteristic of a peer-to-peer decentralised network will empower each participant to easily access data without the need to depend on a central authority for data access. Some interviewees believed that accessing data is vital for collaboration as this would allow for timely retrieval of data or information since it is available to all parties. Extracted comments from a participant which align with the view of enhanced data accessibility include:

"I think the timely retrieval of information will be a major aspect that digital twin and blockchain technology eventually would be able to address."

"You need to focus on specific information that you want stored on the blockchain, but once you have stored the information, then it is available to all the parties involved. So, within the blockchain-enabled digital twin, you would have specific information that is useful for managing the overall lifecycle of the building and are

available to all parties."

The expectation of interviewees is corroborated by Sarfaraz et al. (2023), who revealed that BC poses a potential for ensuring the immutability, validity, and confidentiality of recorded data while enabling decentralised storage. Hence, BC's integration with DT can ensure access to information without a mediator, providing a decentralised solution to project participants. Additionally, the integration of BC and DT can enhance data visibility. Thus, all parties involved in a `built asset's lifecycle can access reliable data on a shared distributed ledger (Suhail et al., 2022).

4.2.2 Data Security

Data Security was also indicated as a key relevant attribute that a BC-enabled DT solution can enhance, resulting in improved collaboration. Most interviewees consider data security very relevant while managing a built asset's lifecycle. In their opinion, a BC-DT integration will ensure data security. Interviewees further indicated that data generated throughout a built asset's lifecycle needs to be protected due to the confidentiality of certain data types shared between project parties. In addition, interviewees highlighted that BC-enabled DT's incorporation into the management of a built asset lifecycle would prevent data from being tampered with due to BC's immutable nature. An extracted interviewee comment is presented below:

"*…but we want to protect this data, and not expose it to any cyber-attacks, or to expose it to people who do not have access to that kind of information. So blockchain data, in the end, will create big changes in how we manage assets, the way we manage the buildings by providing some good data, accurate data, real-time data about the buildings, and that is also secured."*

The views expressed on BC-enabled DT's capability in enhancing data security are corroborated by Shen et al. (2021), who confirmed via a secure data sharing framework that BC's distributed mechanism and cryptographic features can guarantee a higher level of security as compared with a traditional centralised solution. Sahal et al. (2021) revealed that the issue of security in collaborative working could be significantly enhanced by BC-enabled DT due to its potential to allow for secure real-time data exchange and analysis among multiple participants. Data breaches in real-life scenarios highlight the importance of ensuring data security and reliability, hence the need to integrate BC-enabled DT throughout a built asset's lifecycle.

4.2.3 Enhanced Decision-Making

The interviewed participants indicated that the unique characteristics of BC and DT will lead to enhanced decision-making. They highlighted that the feature of DT in providing real-time data on a built asset and BC's capability in ensuring secure, immutable data within a decentralised setting can contribute to timely and accurate decision-making. Additionally, participants revealed that using the real-time data available in BC-enabled DT platform can form a reliable base to improve performance and predict future occurrences. A comment extracted from an interviewee is as follows:

"The strengths of digital twin solutions, with real-time information on the built assets plus the decentralised and transparency strengths of the blockchain technology, I believe that will actually help you to manage facilities better and also, perhaps, generate more insights that can also help improve how facilities are being managed."

Studies by Suhail et al. (2022) have also indicated that integrating BC and DT can ensure that actionable insights are driven by trustworthy data. They further pointed out that BC-enabled DT approach can help stakeholders to acquire more thorough and accurate insights into asset performance based on generated reliable data. Sahal et al. (2021) highlight that BC-enabled DT collaboration can enhance decision-making in avoiding risks and proffer solutions to unexpected occurrences. These studies confirm the views shared by interviewees that incorporating BC-DT creates an enabling environment that can facilitate decision-making in the built environment based on reliable data.

4.2.4 Trust and Transparency

Enhancing trust and transparency between stakeholders involved in a project was also a key perspective shared by most interviewees. A participant believed that BC adds a layer of transparency when integrated into a DT depending on the defined protocols and its peer-to-peer network. Furthermore, participants were of the view that the layer of transparency can contribute to enhancing trust amongst stakeholders. One interviewee stated:

"… it would be that you can trust it because project parties would have the same records. Parties will not be

required to go through old extra records because every time data is updated, it is a universal update throughout the network."

Findings from the interviews are consistent with studies by Teisserenc and Sepasgozar (2021), who posit that incorporating a BC-enabled DT platform is crucial in establishing a reliable and secure data audit trail within decentralised ecosystems, from project initiation to completion. This shared data platform guarantees trust and transparency while ensuring data integrity throughout the project lifecycle. Suhail et al. (2022) suggest that by integrating BC and DTs, all parties involved in a product's lifecycle can effectively and efficiently manage data on a shared distributed ledger, thereby addressing data trust, integrity, and security concerns. In summary, a BC-enabled DT system will enhance stakeholder collaboration, improve transparency, and resolve trust-related concerns.

4.3 Drivers of Blockchain-enabled Digital Twins

Understanding the motivations behind the adoption of digital technologies is crucial, as these drivers can significantly impact behaviour and outcomes (Yang et al., 2021a). This study presents the driving factors, as perceived by key stakeholders, that will lead the AEC-FM industry towards undertaking and successfully executing BC-enabled DT approach. In this context, "drivers" refer to the motivating forces (Opoku et al., 2022) that will prompt stakeholders to execute BC-enabled DT projects effectively. After conducting a thematic analysis of interview data, five key themes emerged as the main influencing factors that would encourage stakeholders in the industry to adopt a BC-enabled DT collaborative approach (see Table 2).

Table 2: Summary of Themes about the Drivers of Blockchain-enabled Digital Twin from Participants

Theme	Descriptions	No of Participants
Affordability and Cost-effectiveness	This theme represents views relating to the cost involved in acquiring the approach and the potential value to be gained	8
Stakeholder Awareness of the Potential Benefits	This theme comprises views relating to stakeholder understanding and perceptions of the benefits	11
Standards, Policies and Regulations	The theme represents views shared on the need for rules, guidelines, and policy interventions.	6
Real-life Implementation	The theme revolves around views shared on the need to showcase practical approaches and demonstrate real-life examples	6
Client's Demands and Interests	This theme encompasses perspectives shared on a client's role and interests	4

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4.3.1 Affordability and Cost-effectiveness

The participants revealed that stakeholders would be more likely to adopt a BC-enabled DT collaborative approach based on its affordability and cost-effectiveness. They mentioned that the affordability of the approach, especially for small-scale industry players, is considered the main driving force behind its development and implementation. In addition, some participants emphasised that a business's decision to invest in a new solution or innovation is primarily influenced by its cost-effectiveness, as businesses constantly strive to make returns on their investments. One interviewee's extracted comment is as follows:

"The main one is the cost to install a big platform. For a small-scale office, it is another cost. So, it only makes sense if the cost return works out. The equity returns on their investment in that platform should justify that investment and make sense if they scale up to larger scale projects for greater returns."

Considering the novelty of a BC-enabled DT approach, its initial cost and affordability are crucial to its potential adoption. Studies by Cheng and Chong (2022) revealed that perceptions about the costs of adopting and implementing emerging technologies can significantly influence stakeholders' adoption decisions. Suhail et al. (2022) pointed out that adopting emerging technologies can help reduce operational costs, reinforce productivity, and enhance operational efficiency. However, industry players still face high initial investments despite the potential benefits gained from their adoption (Toufaily et al., 2021), which could be an obstacle (Rind et al., 2017). Suhail et al. (2022) further suggest that adopting these emerging technologies would require a detailed cost-benefit analysis; otherwise, they may pose a significant challenge to an enterprise's resources.

4.3.2 Stakeholder Awareness of the Potential Benefits

In the AEC-FM industry, BC and DT are emerging technologies many stakeholders may not yet be familiar with. Hence, to promote their adoption, interviewees believe it is important to spread knowledge about their potential benefits. Some interviewees suggest that stakeholders need to be educated and convinced about the added value of these technologies before they can be implemented. The interviewees also underscored the need for continuous advocacy and education to shift the mindset of industry players, especially in an industry that is slow to adopt new technology and where stakeholders may resist new innovations. A typical view shared by interviewees is as follows:

"I believe people need to be convinced that this approach can save them money, make them more efficient, or maybe make them more competitive against their peers or give them some competitive advantage. So, they need to be convinced that investing in tools or new approaches like this will actually be worth it. In the long run, as a business, you don't want to invest your time and resources into something that would actually drain your limited resources. So, people need to be convinced and encouraged to adopt such technologies."

Perspectives shared by participants are supported by Orji et al. (2020), who indicate that having a comprehensive understanding of the advantages of new technological advancements can inspire stakeholders to invest in digital innovations. Therefore, it is recommended that stakeholders who are well-informed about these emerging technologies should emphasise and create awareness of their benefits, such as their ability to improve productivity based on an organisation's resources and traits.

4.3.3 Standards, Policies and Regulations

During the interviews, it was discovered that industry players are more likely to adopt new innovations if stakeholders or policymakers in the built environment develop and implement standards and procedures to guide the adoption and implementation of BC-enabled DT collaborative platforms. The interviewees also highlighted that implementing standards, policies, and regulations would create an environment that enables the proper implementation of new innovations and encourages their adoption. Additionally, some interviewees suggested that the government could spearhead the use of new innovations by establishing and implementing specific project requirements that make adoption necessary. One of the interviewees intimated that:

"So, if the stakeholders or the policymakers in the built environment can come up with standards and procedures, and also give policies and regulations which motivate or promote the adoption of this technology, then it is imminent that professionals in the built environment would definitely adopt it."

The impact of governmental policies, standards, and guidance on the perceived usefulness and complexity of new technologies cannot be underestimated (Cheng & Chong, 2022). Abideen et al. (2022) pointed out that governmental regulations and laws can influence innovation adoption and further cited the 2016 UK construction strategy as a notable instance of such regulations. Hence, regulatory bodies need to create policies and provide support to drive the adoption of BC-enabled DT platform.

4.3.4 Real-life Implementation

Participants suggested that in addition to communication and raising awareness about the benefits of BC-enabled DT platforms, it is important to demonstrate their real-world applications. Most interviewees agreed that developing case studies showcasing the tangible benefits of implementing such platforms would be an effective way to convince industry stakeholders of their value. Some interviewees also recommended creating prototypes to demonstrate the viability of collaborative working using these platforms. Implementing pilot projects was also suggested to illustrate the benefits and encourage adoption. Finally, interviewees emphasised that showing use cases would also educate people about the necessary resources and requirements for successful implementation, given that these technologies are still emerging. One of the interviewees stated that:

"The development of case studies that showed real application of this technology. So, we have to show how these technologies can be applied, and I think that this is the only way in which we can prove to industry and academia the values and the benefits that we can realise using the integration of BC and DT."

The views expressed by interviewees are further supported by Zhang et al. (2023), who suggest that pilot projects are a practical approach to tackling technical concerns that stakeholders may have and enhance their appreciation of the advantages of implementing emerging technologies. They further pointed out that many stakeholders hesitate to embrace new technologies because they lack real-world case studies to prove their effectiveness. Hence, the deployment of pilot projects cannot be discounted as a driving force during decision-making in adopting digital solutions.

4.3.5 Client's Demands and Interests

Interviewees emphasised the role of the clients or owners as driving forces in adopting innovation. They explained that clients have the potential to fuel innovation through their desire to explore novel approaches and optimise project execution methods. Additionally, interviewees confirmed that some clients often support new strategies that can motivate adoption. However, some interviewees caution that clients without knowledge of new technologies or a clear understanding of their needs may demand unrealistic solutions. An interviewee shared the view that;

"So basically, what I'm trying to say is that professionals and clients that would love to see new ways and better ways of doing things will easily find this approach very valuable to them."

Similar studies on the adoption of digital technologies corroborate the role of the client as an important driver. According to Yang et al. (2021b), increasing market demands for digitalised solutions in many industrial disciplines have driven firms to adopt digital technologies to meet client demands and requirements and maintain client relationships. Abideen et al. (2022) also pointed out that industry professionals are driven by clients' awareness of potential enhancements in the digital built environment, and this usually motivates industry players to achieve competence and excellence when adopting and implementing new solutions.

5. CONCLUSION

This paper explored the perspectives of industry and academic professionals about the potential roles that BC-enabled DT collaborative approach could play in the AEC-FM industry, as well as the influencing drivers that would motivate such stakeholders to pursue BC-enabled DT approach to collaborative working. Emerging themes from respondents revealed that participants perceived that BC-enabled DT could create an enabling environment for enhanced data accessibility, data security, enhanced decision-making, and promote trust and transparency, thus making it vital for collaborative work across the AEC-FM industry. Meanwhile, it was discovered that five main factors emerged from participants' responses as motivational drivers to pursue the path of BC-enabled DT; these are affordability and cost-effectiveness, stakeholder awareness of the potential benefits, standards, policies, and regulations, real-life implementation, and client's demands and interests.

Despite BC-enabled DT solutions being explored in other industries for collaborations, the lack of attention to its combined potential in the AEC-FM leads to the heart of this study's novelty, which lies in its focus on empirically identifying its anticipated roles and influential drivers. By conducting semi-structured interviews with industry and academic practitioners, the findings are expected to resonate with readers who seek to understand key considerations that come into play beyond the promised potential within literature.

A significant limitation of this study was the difficulty in finding participants with knowledge or experience in both BC and DT applications to respond to the study's questions.

Based on the findings of this study, it is recommended that further empirical investigation be conducted to gain a holistic understanding of the capabilities and implications of adopting a BC-enabled DT approach to address the collaboration challenges inherent in the AEC-FM industry as it gears up towards embracing digital transformations.

6. ACKNOWLEDGEMENT

This paper contains research which is part of the lead author's ongoing PhD research project, partially funded by Teesside University.

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BLOCKCHAIN-BPMN INTEGRATED FRAMEWORK FOR CONSTRUCTION MANAGEMENT

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ABSTRACT: *Implementing blockchain benefits various construction management processes, such as securing payments, enabling traceable design process, and enhancing information transparency in supply chain. However, blockchain implementation in construction is still in its infancy due to weak functionality of smart contracts, which are self-enforceable programs allowing iteration between external data and blockchain. In the context of construction management that embraces complex and dynamic business processes, smart contracts are currently designed based on specific and isolated functional requirements without considering the connection and execution logic between these functions. It leads to inefficient collaboration and even execution errors, thereby corrupting data quality and even causing business failure. Therefore, this paper proposes a Blockchain-BPMN (Business Process Model and Notation) integrated (BBI) framework for construction management. The framework poses two contributions. First, a BPMN-driven method is developed to design smart contracts supporting executing linked and logically connected business activities. Second, an access control strategy is integrated into smart contracts to safeguard the accessibility of sensitive business data in a blockchain environment. The BBI framework is validated in an actual BIM design collaboration scenario, and results show its feasibility and computational performance are acceptable. Several aspects for improvement and future directions are discussed in the end.*

KEYWORDS: *Smart contract; Blockchain; BPMN; Construction business process*

1. INTRODUCTION

Data security is becoming an increasingly concerning issue in the construction industry. With the higher level of digitalization in construction, it is inevitable that data security becomes more important (García de Soto et al., 2022). Several examples highlight the vulnerabilities that exist in the construction business process, such as the lack of records for Building Information Modeling (BIM) changes, fragmented and unaccountable supply chains, and insecure payment systems. These vulnerabilities can result in various negative consequences for construction projects, from delays and cost overruns to compromised safety and quality. Therefore, it is crucial for the construction industry to prioritize data security, traceability, and process automation. By implementing robust security measures, ensuring transparency and accountability in the supply chain, and automating processes, construction companies can mitigate the risks associated with data breaches and cyberattacks. This not only protects sensitive information but also improves overall project efficiency and reduces the likelihood of errors and disputes. The construction industry must recognize the importance of data security and take proactive steps to safeguard their systems and information.

Blockchain and smart contracts have emerged as potential solutions to various challenges in different industries, including the construction sector. Blockchain is a decentralized digital ledger that records and verifies transactions across multiple computers, ensuring transparency, security, and immutability (Leng et al., 2022). On the other hand, smart contracts are self-executing contracts executed in the blockchain platforms with the terms of the agreement directly written into lines of code (Ye et al., 2022a). These two technologies have the potential to revolutionize the way transactions are conducted and contracts are executed.

In the construction industry, blockchain and smart contracts have been explored as solutions to various problems. One example is payment management. Smart contracts can automate the payment process, ensuring that contractors and suppliers are paid promptly based on predefined conditions (Sigalov et al., 2021; Ye & König,

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Xuling Ye, Xingyu Tao, Jack C. P. Cheng, Markus König, *Blockchain-BPMN Integrated Framework for Construction Management,* pp. 309-317, DOI 10.36253/979-12-215-0289-3.29

2021a; Ye et al., 2020). Another example is in the field of BIM change record in the design phrase. By implementing smart contracts, any modifications to the design of BIM model can be automatically updated to blockchain, ensuring that all stakeholders are aware of the changes and can plan accordingly (Xue & Lu, 2020). This can help streamline the design phase and minimize the risk of errors or miscommunication. Supply chain management is another aspect of the construction industry that can benefit from blockchain and smart contracts. With complex supply chains involving multiple suppliers, contractors, and subcontractors, ensuring transparency and traceability becomes crucial. Blockchain can provide a secure and immutable record of every transaction and movement of materials, enabling stakeholders to track the origin, quality, and location of construction materials, where smart contracts can automate the procurement process, ensuring that materials are ordered and delivered on time, and payments are made only after satisfactory delivery (Elghaish et al., 2023). Therefore, blockchain and smart contracts have the potential to revolutionize the construction industry by addressing various challenges and improving efficiency. As more research and implementation examples emerge, these two technologies are not just buzzwords but practical solutions that can drive innovation and transformation in the construction industry. However, the current smart contract implementation is isolated, neglecting task sequence execution, leading to limited automation. Furthermore, the use of code in smart contracts makes them challenging to understand for non-programming participants in the construction industry.

Therefore, the main objectives of this study are to explore the possibility of incorporating blockchain and smart contracts into construction business processes and to improve the automation level using smart contracts in the construction field. To achieve these, we propose a novel BPMN-driven approach aimed at enhancing the efficiency and automation capabilities of smart contracts. The study aims to develop a Blockchain-BPMN integrated framework for connected smart contract execution, enabling seamless interaction and collaboration among different smart contract functions, thereby automating complex construction workflows. Additionally, a smart contract access control strategy is proposed to manage data accessibility, ensuring that sensitive information is only accessible to authorized parties while maintaining transparency.

2. LITERATURE REVIEW

2.1 Blockchain and smart contracts in construction

In the construction industry, many blockchain and smart contract reviews were conducted and their adoption to the construction industry were highlighted. For example, the applications of blockchain and smart contracts in construction were summarized by Li and Kassem (2021), which mainly focusing on information management, payment, procurement and supply chain management. Another smart contract review was conducted, which pointed out that 81 smart contract-related papers were published from 2014 to 2021 in the construction industry, focusing on the areas of contract and payment, supply chain and logistic, and information management (Ye et al., 2022a).

One of the critical pain points in the construction industry is the inefficiency and lack of transparency in payment processes. Smart contract-based payment systems have emerged as a promising approach to tackle these issues. Ahmadisheykhsarmast and Sonmez (2020) investigated the implementation of smart contracts in construction projects to enhance security in payment processes. Their study demonstrated that smart contracts could automate payment release based on predefined conditions, reducing payment delays and disputes significantly. Building Information Modeling (BIM) is a critical component of the construction process, allowing stakeholders to collaborate visually and efficiently during the design phase. Integrating blockchain technology with BIM has the potential to enhance data management and collaboration (Ye et al., 2022b). Tao et al. (2021) explored the use of blockchain and smart contracts for BIM-based collaborative design in construction projects. Their research demonstrated that the decentralized and immutable nature of blockchain improves data sharing and coordination among stakeholders during the BIM design phase.

The current use of smart contracts faces limitations, including their isolated nature and the absence of a coherent approach to developing logical methods that align with construction business processes. In Fig. 1, a comparison highlights the difference between the current practice and the potential capabilities of smart contracts in construction workflows. Presently, various tasks are handled by independent smart contracts, necessitating users to determine which contract to engage. For instance, in Fig. 1(a), tasks are individually managed by separate smart contracts without intrinsic connections, which may cause execution or business logic errors and decrease the automation level of smart contracts. The current practice contrasts with practical expectations where inter-dependencies should be embedded. Fig. 1(b) illustrates the expectation for execution tasks within a smart contract, which enhancing the automation potential of smart contracts.

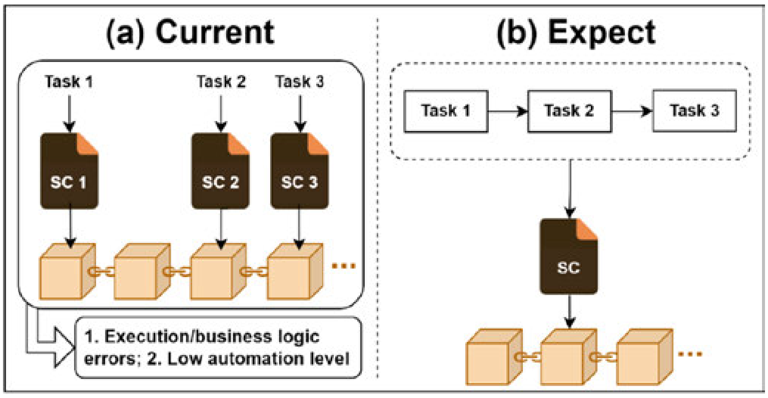

Fig. 1: The limitation of the current usage of smart contracts. (a) Current practice of smart contracts; (b) Expected usage of smart contract

2.2 Combination with BPMN for construction business process management

Business Process Model and Notation (BPMN) is a standardized graphical representation language used to define and visualize business processes (Object Management Group, 2013). In the realm of construction project management, BPMN offers a range of benefits. It provides a clear and intuitive visualization of complex construction workflows, enabling stakeholders to understand processes more easily (Borrmann et al., 2018). This enhances communication, collaboration, and decision-making among project teams. Furthermore, BPMN can facilitate the identification of bottlenecks, inefficiencies, and potential improvements in construction processes, contributing to more effective project management and resource allocation (Borrmann et al., 2018).

BPMN's suitability for connecting smart contracts is noteworthy. With its versatile graphical representation, BPMN can model and illustrate the interactions between different smart contract functions effectively. This enables the design of intricate sequences of smart contract executions, facilitating the automation of multi-step processes (Ye & König, 2021b). For example, López-Pintado et al. (2019; 2022) introduced and implemented a blockchain-based BPMN execution engine called Caterpillar to generate smart contracts using a BPMN-to-solidity compiler. Di Ciccio et al. (2019) proposed an approach to translate from BPMN process models to smart contracts using Caterpillar tool, execute processes through smart contracts, and track activities in the Ethereum blockchain. The other existing study in the construction industry analyzed the possibilities of combining blockchain and BPMN choreographies, and proposed a framework to identify the state of each process in BPMN processes and choreographies (Spalazzi et al., 2021). Additionally, BPMN can be coupled with access control mechanisms, ensuring that only authorized parties can engage with specific smart contracts or process steps. This integration strengthens security and transparency, both crucial aspects in the construction domain.

However, the current research focuses on direct translation from BPMN to smart contracts, without considering the real-time connection and visual execution of BPMN and smart contracts. One reason is the relative novelty of blockchain and smart contract adoption within business processes. As a result, the exploration of BPMN's capabilities for this purpose is limited. Moreover, incorporating access control mechanisms in this context presents challenges, as construction projects involve various stakeholders with differing levels of authorization. Balancing data visibility and access becomes intricate, given the diversity of involved parties and the need to maintain data integrity and security.

This paper addresses these gaps by presenting two significant contributions. Firstly, it introduces a groundbreaking Blockchain-BPMN integrated framework designed for the connected execution of smart contracts. This framework allows for the seamless interaction and execution of interconnected smart contracts, enabling the automation of complex construction workflows. Secondly, the paper proposes an innovative smart contract access control strategy that caters to the diverse data visibility needs of various stakeholders in the construction process. These contributions collectively aim to revolutionize the construction industry's approach to business process automation, improving efficiency, transparency, and collaboration through the integration of BPMN and blockchain-powered smart contracts.

3. METHODOLOGY

The research methodology, illustrated in Fig. 2, comprises three key steps. Step 1 involves designing a Blockchain-BPMN integrated (BBI) framework by firstly defining the framework's logic and workflow, and then explaining how the connected smart contracts are executed in the framework. Step 2 focuses on developing a strategy to control data access. This includes determining who can see which data level based on permissions and setting rules for accessing data stored both inside and outside of the blockchain. In Step 3, the logical smart contract algorithm is developed, by defining the mapping from BPMN to smart contracts, and developing the smart contracts based on the BPMN execution logic. The output of Step 1 is a concept explanation of the BBI framework, and its functionalities are detailed further by the development of the data access control strategy in Step 2 and the logical smart contract algorithm in Step 3. Step 4 tests the feasibility of the BBI framework using a case study. This includes building and putting the BBI framework into action, and then assessing its effectiveness using a BIM-based design collaboration scenario.

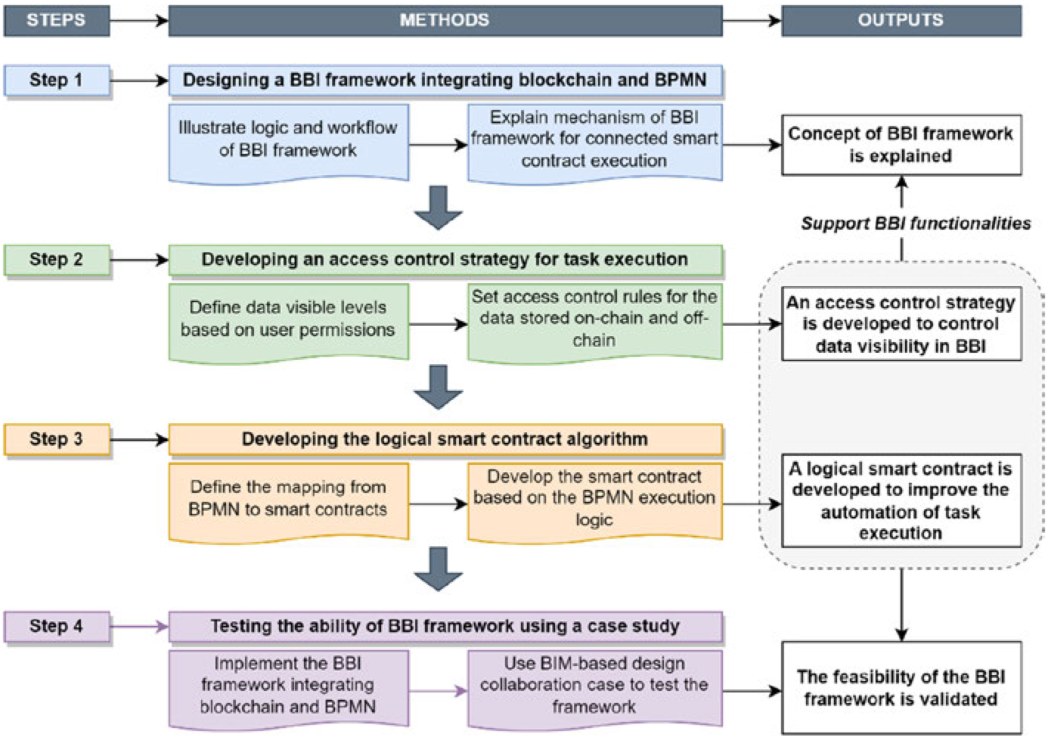

Fig. 2: Research methodology

3.1 Blockchain-BPMN integrated framework

The overview of the proposed BBI framework is shown as Fig. 3. Process-embedded smart contract list (PeSCL) is proposed in this paper for storing all the process-required data in a construction project to be executed via the smart contracts, which includes such as project information, participant information, process units, and the linkage to the BIM model. The PeSCL and the BIM model are the inputs for the framework (Fig. 3①), where BIM model is displayed in a BIM viewer, and PeSCL is displayed as table. They are linked via the GUID of each BIM elements that stored in the PeSCL (Fig. 3②). These two input data are further linked with the construction business process, which is represented by BPMN (Fig. 3③). Each BPMN task is mapped to a corresponding smart contract function. Real-time process visualization and execution are then realized (Fig. 3④). During the task execution, an access control strategy is developed for controlling different data permissions for different participants of the construction project. Such strategy controls the visible level of both on-chain and off-chain data (Fig. 3⑤). The logical smart contracts automatically execute the tasks represented via BPMN with their execution logic, and their transactions are stored in the blockchain (Fig. 3⑥). Such framework can not only visualize BIM and real-time construction business process execution status with an improvement of business process automation, but also build trust and realize data access control.

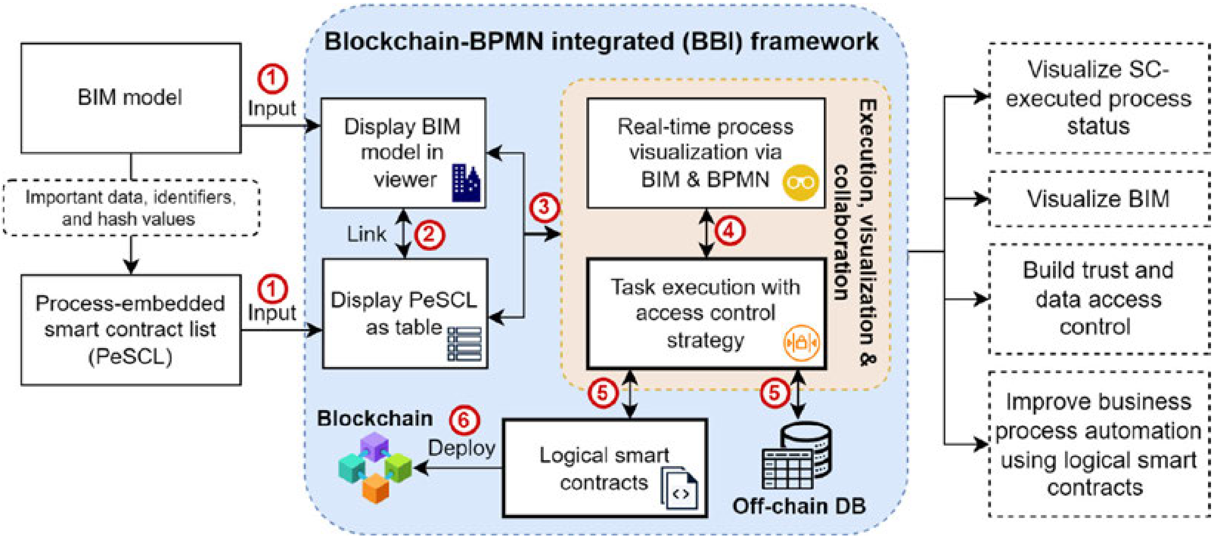

Fig. 3: The overview of the proposed Blockchain-BPMN Integrated (BBI) framework

3.2 On-chain and off-chain access control strategy

The access control strategy can be divided into two parts, namely on-chain and off-chain data access permission (see Fig. 4). All the project-related documents are stored in the off-chain storage, where the permission level of each document is also stored. When users request to check or modify the off-chain data, their username (as identifier) and permission level will be firstly checked. All the sensitive or valuable data are stored on-chain (i.e., on the blockchain), and only specific user can call specific smart contract functions. When users request to view or modify the blockchain (BC) data, their BC account identifier will be firstly checked in their called smart contract function for viewing or modifying request. Further detailed example about the access control strategy is shown in the case study section (Section 4).

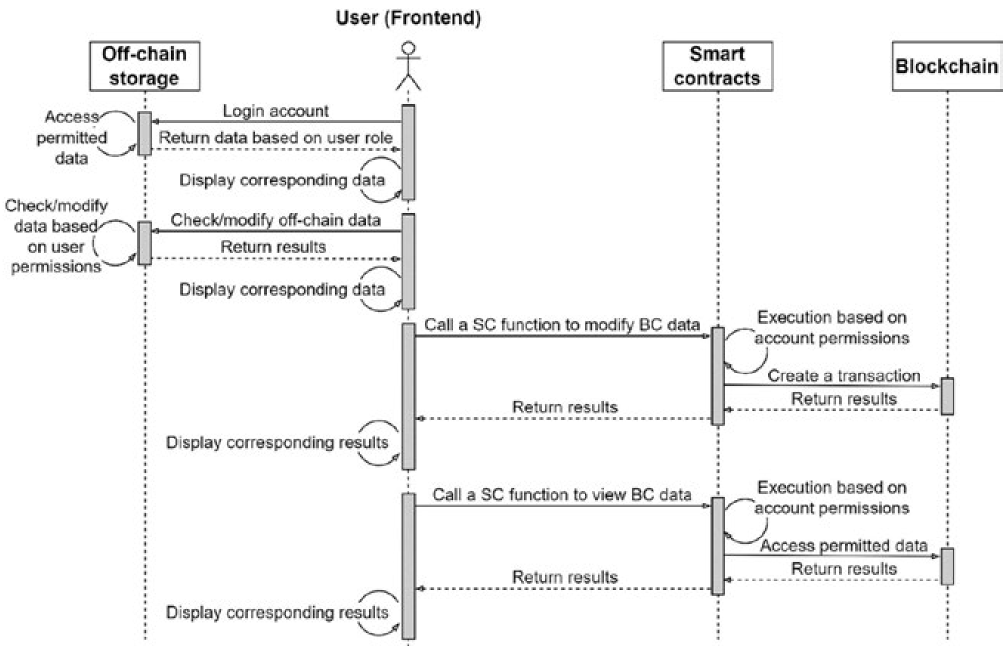

Fig. 4: Access control strategy among users, smart contracts, blockchain, and off-chain storage

3.3 From BPMN to logical smart contract

To solve the problem of current isolated smart contract usage, this paper proposes a way of implementing smart contracts, which is defined as logical smart contracts. Such logical smart contract, which is interpreted based on the BPMN components, not only automates the BPMN tasks based on the execution logic in BPMN, but also further automates the inner actions of some specific BPMN tasks. The mapping from BPMN to the logical smart contract is shown as Fig. 5. In BPMN, there are three main components, namely participants, tasks, and flows. BPMN participants are interpreted into P.StateVariables and P.Modifiers, where the former is used to store the information of the participants (such as identifier and role) and the latter is used to restrict that only specific participant can execute specific smart contract function (for access control strategy). BPMN tasks include task participants and inner actions, where the former is from the BPMN participants with the specific task execution permission and the latter is to indicate what actions could be done within the tasks. BPMN flows are used to indicate the execution logic of BPMN tasks, which is further interpreted into F.StateVariable, Enum, F.Modifiers and F.Functions. Further example of the generated logical smart contract is shown in the case study.

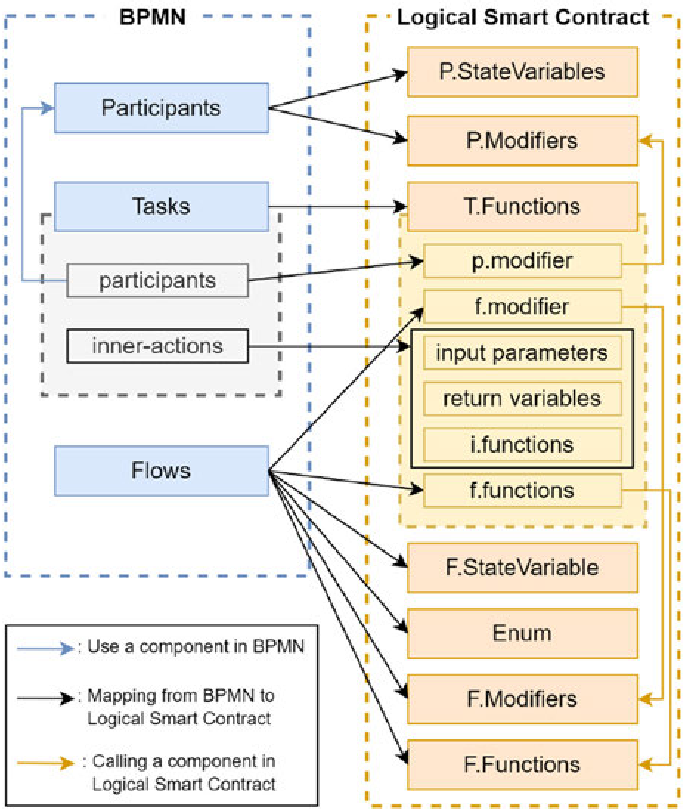

Fig. 5: Mapping from the logic of BPMN to the logical smart contract

4. CASE STUDY

Validation of the proposed BBI framework was achieved through the implementation of a decentralized application, where a React frontend was seamlessly integrated with the Ethereum blockchain. This implementation was rigorously tested against a real-world BIM design collaboration case from Tao et al. (2021). In Fig. 6, the comparative analysis between their original smart contract solution and our enhanced logical smart contract is presented, revealing the improvements achieved by integrating process logic into the smart contract. Following this comparative analysis, the testing results of the case within our implementation are diligently presented in Fig. 7, providing a comprehensive view of the real-world applicability and efficacy of our proposed framework.

In Fig. 6(a), the BPMN workflow was meticulously designed based on the case elucidated by Tao et al., encompassing three distinct roles of participants and a comprehensive set of seven BPMN tasks. Fig. 6(b) depicts the original smart contract solution, which was rather limited, accommodating only two smart contract functions, namely UPLOAD and INQUIRE. In this solution, real-time process status updates were unavailable to participants, and the execution of smart contract functions required manual intervention from the participants themselves, lacking the seamless automation sought after. Conversely, in Fig. 6(c), our proposed logical smart contract solution represents a significant advancement. Execution logic and access permission are ingeniously incorporated directly into the smart contract, improving its ability for automation and collaboration. Furthermore, execution permissions are elegantly restricted by this design, significantly mitigating the potential for errors and associated challenges, thus providing a more robust and efficient solution for BIM design collaboration in the smart contract system.

Fig. 7 serves as a comprehensive visual representation of the final case outcomes, encapsulating a multitude of crucial components that harmoniously contribute to the success of our BBI framework. Within this illustrative figure, Fig.7(a) provides an immersive real-time visualization of the BPMN process status, meticulously denoting task execution through distinct markers, with yellow indicating completed tasks and green designating those currently in progress. This dynamic display offers stakeholders an intuitive and up-to-date overview of project progression. In Fig.7(b), the logic of BPMN tasks is revealed through the logical smart contract functions, showcasing how these functions govern the execution of critical project activities.

Meanwhile, Fig.7(c) introduces the access control strategy with strict user authentication via blockchain login accounts. This authentication process ensures varying levels of data visibility across the frontend, catering to the unique needs and privileges of individual users. Furthermore, it plays a pivotal role in safeguarding sensitive smart contract functions, allowing access only to authorized stakeholders. The BIM model is displayed in Fig.7(d) through the BIM viewer, providing stakeholders with a comprehensive visual representation of the project's architectural intricacies. This model is intimately linked to the PeSCL shown in Fig.7(e) , which is used for storing and listing project-specific details. Finally, Fig.7(f) focuses on on-chain data and blockchain-related information, demonstrating the transparent and immutable nature of data stored in the blockchain. Together, these components provide project participants with valuable insights into the structural and organizational dimensions of the project, offering a holistic view of how blockchain-based smart contracts enhance transparency and data integrity in the BIM design collaboration case.

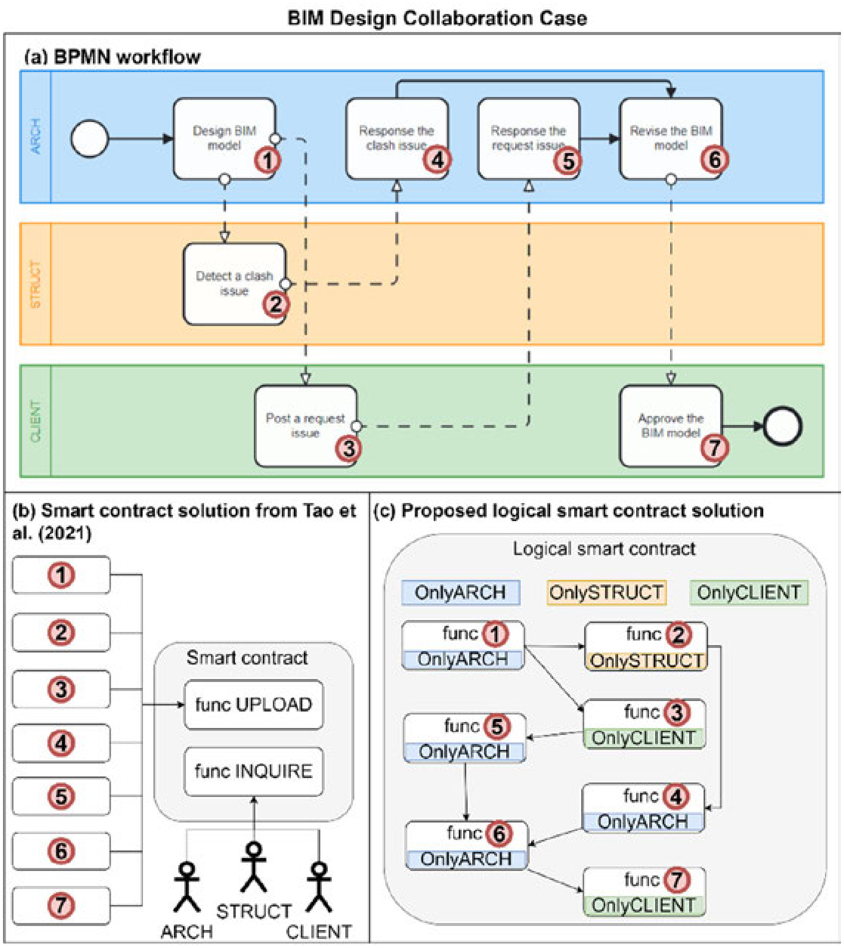

Fig. 6: The comparison of (b) the smart contract from Tao et al. (2021) and (c) the proposed logical smart contract

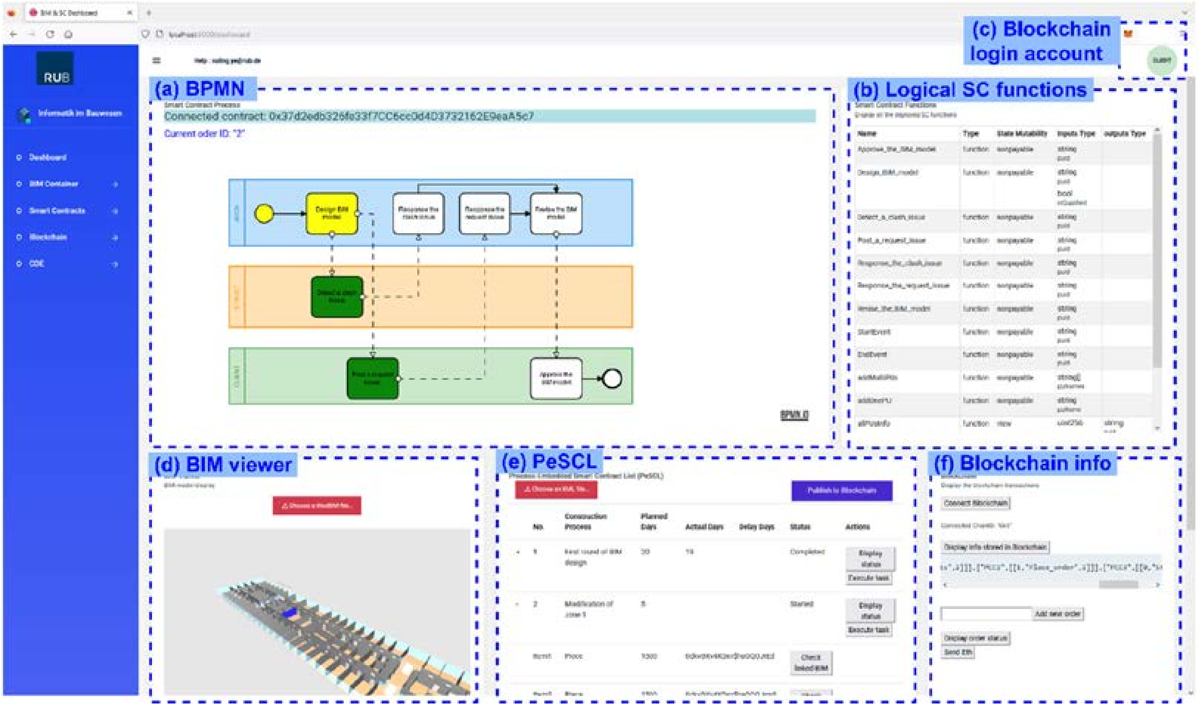

Fig. 7: Results of the BIM design case in the BBI framework

5. CONCLUSION

In summary, the escalating concern for data security in construction business processes has spurred the search for innovative remedies. While the potential of Blockchain and smart contracts is evident, they grapple with substantial drawbacks, notably the isolation of current smart contract implementations and the difficulty non-programming participants face in comprehending smart contract codes within the construction industry. This study has confronted these challenges head-on by pioneering a BPMN-driven approach, seamlessly integrating blockchain and smart contracts while remedying issues related to automation and participant understanding. The introduction of the Blockchain-BPMN integrated (BBI) framework marks a significant advancement, revolutionizing the automation of intricate construction workflows, fostering seamless collaboration, and enhancing visualization across diverse smart contract functions. The strategic inclusion of an access control strategy fortifies data security while preserving transparency. The innovation of logical smart contracts, enhancing automation by embedding task execution flows, is a notable contribution. The feasibility and efficacy of the BBI framework are demonstrated through practical implementation and rigorous testing in a BIM design collaboration scenario. However, a lingering limitation pertains to the immutability of smart contracts. Future endeavors should focus on enriching the framework's adaptability and addressing this issue by incorporating an upgradable feature into the proposed logical smart contracts, paving the way for more refined solutions to the multifaceted challenges inherent in the construction field.

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FAST AND SECURE BIM DESIGN USING BLOCKCHAIN: AN EXAMPLE OF MAKESHIFT HOSPITAL PROJECT FOR COVID-19 TREATMENT IN HONG KONG

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ABSTRACT: *A crucial action of COVID-19 combat is the quick design and building of makeshift hospitals (MHs). Although adopting building information modeling (BIM) promotes the digitalization and communication of design collaboration, data security vulnerabilities (e.g., lacking traceability and transparency) are detected and have inevitably impeded the efficiency and productivity of the MH project. Such problems often lead to rework and unnecessary disputes, wasting valuable time on projects requiring ultra-fast construction speed. The emerging blockchain technology offers an immutable and traceable collaboration environment. However, limited studies have integrated blockchain in the BIM design process, especially design in emergency projects like MH. Therefore, this paper proposes a blockchain-enabled collaboration (BEC) framework for fast and secure BIM design. The framework is illustrated in an actual MH project in Hong Kong, and results show that: (1) it supports secure and automated BIM data exchange and (2) it saves 23 % of the time in a design coordination case.*

KEYWORDS: *Covid-19, BIM, Blockchain, Makeshift Hospital, Smart Contract.*

1. INTRODUCTION

The COVID-19 pandemic seriously threatens the global public medical and health system. By January 2023, there had been over 750 million confirmed illnesses and over 6 million documented fatalities (WHO, 2023). Governments launched many emergency construction projects to meet the enormous demand for patient quarantine facilities, establishing multiple makeshift hospitals (MHs) (Luo et al., 2020). A makeshift hospital, also referred to as Fangcang hospital or mobile cabin hospital, is a type of emergency service that assembles modular medical units to form a temporary hospital to address the ongoing scarcity of medical supplies. Two examples in China, Huoshenshan hospital and Leishenshan hospitals, built and delivered in 10 days and 18 days, respectively, have proved that the suppression of epidemic outbreaks is made possible by establishing temporary MHs, which are crucial for lifesaving and improving recovery rates (Zhou et al., 2022).

MHs have challenging tasks, intricate specifications, and condensed design and build times. Therefore, building information modeling (BIM) technology is introduced because these criteria present additional difficulties for design work (Tan ey al., 2021). BIM is essential in streamlining coordination by combining organizational and procedural data into a shared repository. According to (Luo et al., 2020), BIM benefits the MH design in three aspects. First, MH design needs significant optimization work by reducing changes during the building phase by visualizing all conflicts. Additionally, designers can use integrated BIM data to speed up construction for parallel scheduling, improving design simulation, like predicting the transmission of viruses in negative pressure wards. Finally, BIM is a platform everyone can use to easily create, exchange, and collect digital data to promote collaboration.

However, some data security concerns still exist in the MH BIM process, causing reworks and time waste, hindering efficiency and productivity. For example, in contrast to general construction projects in which BIM models from various disciplines are created sequentially, models in MHs are made independently and concurrently. When BIM information is synchronized amongst teams, there is a danger of data omission and inconsistency, which eventually leads to design errors because there are no referenced models for the untransparent collaborative environment. Besides, there are no routine meetings for BIM coordination due to time constraints. Instead, a "peer-to-peer (P2P)" communication model is used, wherein project members contact accountable designers directly and personally through virtual meetings or phone calls. However, because it lacks verifiable and traceable records, this method can occasionally be disorganized and ineffectual, making collaboration time-consuming.

Blockchain is a distributed database technology that leverages peer-to-peer networks, cryptographic hash algorithms, and consensus mechanisms to secure data integrity (Tao et al., 2020). The blockchain prevents a single

Referee List (DOI: 10.36253/fup_referee_list)
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Xingyu Tao, Xingbo Gong, Moumita Das, Yuqing Xu, Hao Liu, Jack Cp Cheng, Chengliang Zheng, *Fast and Secure BIM Design Using Blockchain: An Example of Makeshift Hospital Project for COVID-19 Treatment in Hong Kong,* pp. 318-326, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.30

administrator from controlling the entire network because each peer keeps an identical and append-only data copy (also known as the blockchain ledger). The benefits of blockchain in construction payment (Das et al., 2020), supply chain management (Tezel et al., 2021), and design collaboration (Pradeep et al., 2021) have been preliminarily investigated. However, incorporating blockchain into MHs is still in its infancy for two barriers: (1) The mechanism of embedding blockchain in an MH BIM process is unclear. Problems like which activities need blockchain and what data should be transferred are still awaiting solutions. (2) Key technical elements, like smart contracts supporting blockchain data interaction, have not been developed.

Therefore, this paper proposes a blockchain-enabled collaboration (BEC) framework for fast and secure BIM design. The primary scientific contributions of this paper are: (1) identified three main security risks in the MH BIM design process, (2) proposed a BEC framework to alleviate harms brought by the security issue, thus improving design efficiency, and (3) developed three smart contracts to automate the data exchange in a blockchain. Finally, the framework is demonstrated and evaluated in an actual MH project in Hong Kong.

2. METHODOLOGY

2.1 Identification of BIM security vulnerabilities in MH

Locating the risks is the fundamental step in developing the BEC framework. In this study, one BIM manager and two BIM designers who had a direct hand in an MH project and were familiar with the intricate steps of BIM-based design were interviewed four times each. Data collection took place over one month in 2022, from March to April. A BIM collaborative design workflow is in Figure 1.

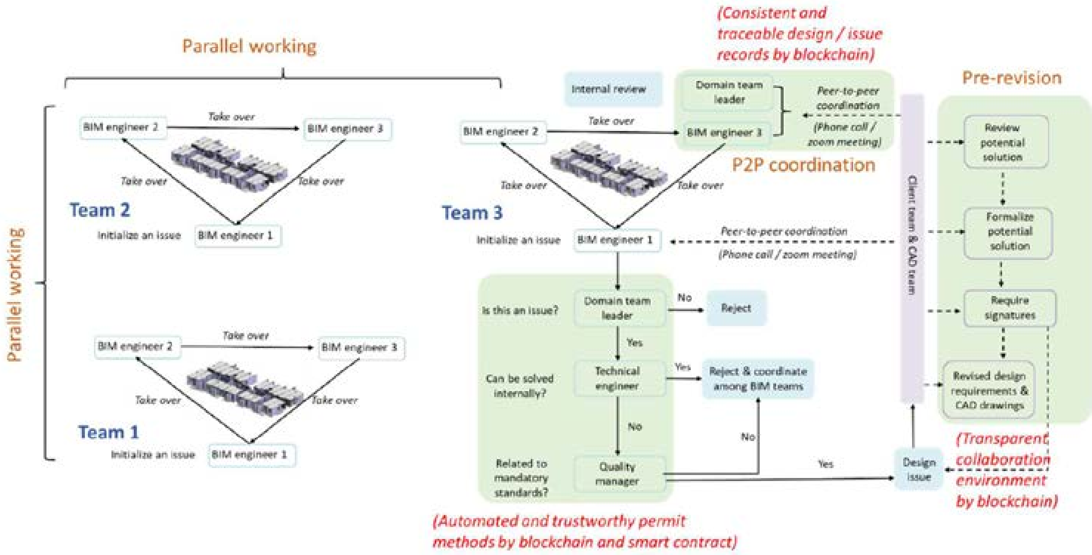

Fig. 1: BIM-based design workflow in MH

Three factors account for how the workflow quickens the BIM design process. The parallel design is the first benefit. Several models are produced simultaneously in this MCH project, reducing time compared to normal construction projects in which BIM models from several disciplines are developed sequentially. P2P communication is the second advantage. There are no scheduled meetings for BIM coordination because of scheduling constraints. Instead, a P2P communication model is used, in which accountable designers are contacted directly and personally by project members during virtual meetings or phone calls when design issues arise. This is an effective method for facilitating communication since it prevents pointless meetings and enables responsible individuals to identify design concerns promptly. Pre-revision refers to addressing design or BIM model issues before the client issues formally amended drawings or documentation, saving waiting time. Content marked green in Figure 1 indicates the steps that can be improved by blockchain.

However, security flaws are also caused by such unique collaboration methods. The risks and merits provided by blockchain are presented in Figure 2. For parallel work, the absence of a visible path for updating information causes differences across models, mistakes in design, and even delays. Blockchain guarantees data transparency and consistency thanks to its distributed architecture. In the course of the discussion, the BIM manager bemoaned the fact that they frequently wasted time looking up design records to identify problems because ECPs lacked adequate logging facilities, leaving out certain previous data. Additionally, several designers collaborate to develop a model in a "relay race" fashion, with each team member finishing a section of the model in turn. The designer contacted during the P2P collaboration may not be aware of the specifics of the issue if they recently took over the contract from another designer (the issue proposer). All design logs and actions can be immutably recorded using blockchain to improve collaboration traceability.

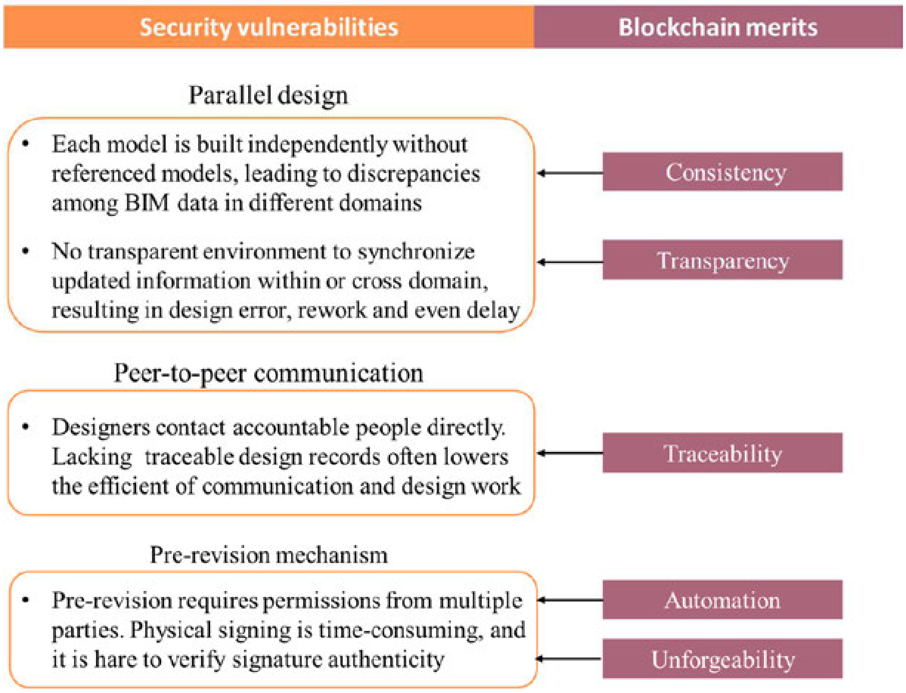

Fig. 2: Blockchain merits in MH

2.2 Blockchain-enabled collaboration (BEC) framework

The BEC framework in Figure 3 shows the logic of implementing blockchain in an MH BIM design and offers a technical stack for data flow. The seven-layer architecture serves as an example of the technical stack used to create a BEC framework. Through the application layer, which provides an interface for user management, users in the user layer can sign up for the blockchain. User operations may be documented in the blockchain in this manner. These "one-stop" registration processes make it easier for consumers to use blockchains because they simply need to complete standard registration processes. The interaction between the front-end inputs and the blockchain databases on the backend is carried out through smart contracts at the smart contract layer. Blockchain smart contracts, machine-readable pieces of code, can self-execute business logic (e.g., payment) on blockchain ledgers, thus empowering automatic and unforgeable collaboration actions (Li et al., 2022). Event transactions will represent collaboration actions, such as permission transactions (metadata of permission execution), issue event transactions, and model event transactions (metadata of events pertaining to BIM models). Large-sized data like BIM models and non-graphic documents are also stored in off-chain databases, which can be local servers or cloud servers like Autodesk BIM 360. This is in addition to on-chain data (transactions). This layer has a digital signature generator that generates digital signatures using the 256-bit secure hash technique (SHA-256). These fingerprints are spread across the blockchain network. The infrastructure layer serves as the foundation and provides necessary services, including cloud data storage, operating systems, and hardware (e.g., GPU and CPU).

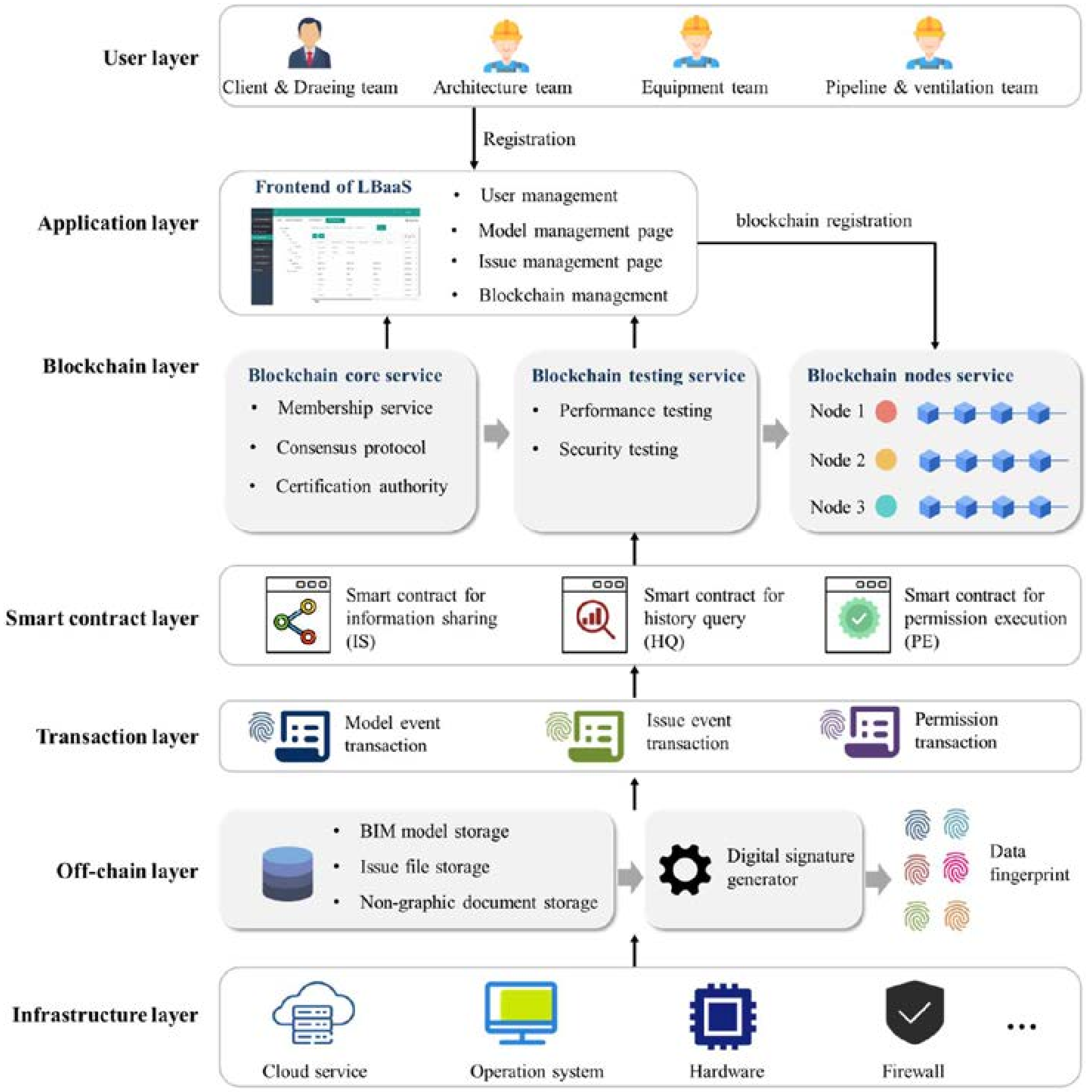

Fig. 3: Architecture of BEC framework

2.3 Smart contracts for BIM data interaction

In the BEC framework, three smart contracts have been coded. The pseudocodes are shown in Figure 4. A transaction comprising the model ID, fingerprint, user ID, and timestamp will be transmitted to the IS (information sharing) smart contract whenever a user uploads a new model (or issue). An endorsing node will verify this transaction by examining the legality of the transaction (Step 1). Illegal transactions will be denied, or they can go through and be sent back to the smart contract with endorsing signatures. An example of an illegal transaction would be one where the transaction data model is not required to follow a key-value structure (Step 2). In Step 3, the smart contract hands the transaction off to an ordering service that will chronologically group the transactions that occurred within the specified time into a new block. All blockchain nodes will receive it through the smart contract, and upon obtaining it, they will verify the block (Steps 4 and 5). The ledger will be updated with confirmed blocks as immutable records.

The rationale behind PE (permission execution) smart contracts is similar. One distinction is the smart contract input, and the other is the status results. After reviewing an issue, a project member (such as a domain manager) can decide. An endorsing peer will receive a new transaction from the PE smart contract along with all essential metadata (such as issue ID, issue decision, reviewer comments, etc.) so they can verify that the input complies with the regulated data model. Then, the project member will update the blockchain world state, a database that displays the most current status of various files and is built on top of the blockchain ledger. Besides, the PE smart contract creates and stores the digital signatures of the user to ensure the integrity of outcomes, saving time by doing away with the laborious physical permit process. The HQ (history query) smart contract will retrieve previous transactions (e.g., file ID) based on the provided key.

Pseudocode of information sharing (IS) smart contract

```
Input: IS transaction data, IS function
Output: New block in blockchain
Step 1: IS function proposes the transaction for legality checking
    if input data model = pre-defined IS data model
        Function name = IS
        generate endorser signatures
    else
        validation fails
Step 2: Get back endorsing signature
        return pre-execution results ← transaction data||read-set||write-set||signatures
Step 3: Sent to ordering service for new block packing
    new block ← pre-execution results||block hashes||Merkle tree||timestamp
Step 4: Broadcast the new block to all nodes
Step 5: Verify and add to ledger
    if validation results = true
        return new block ← block number "N+1"
        notification message ← "Transaction has been successfully shared"
    else
        IS transaction sharing fails
Step 6: Notification
End
```

Pseudocode of permission execution (PE) smart contract

```
Input: PE transaction data, decision, PE function
Output: New block in blockchain, issue status change
Step 1: PE function proposes the transaction for legality checking
    if input data model = pre-defined PE data model
            Function name = PE
            generate endorser signatures
    else
            validation fails
Step 2: Get back endorsing signature
        return pre-execution results ← transaction data||read-set||write-set||signatures
Step 3: Sent to ordering service for new block packing
        new block ← pre-execution results||block hashes||Merkle tree||timestamp
Step 4: Broadcast the new block to all nodes
Step 5: Verify and add to ledger
        if validation results = true
            return new block ← block number "N+1"
            notification message ← "Transaction has been successfully shared"
            New issue status ← reviewer ID||decision
        else
            PE transaction sharing fails
Step 6: Notification
End
```

Pseudocode of history query (HQ) smart contract

```
Input: Target file ID, HQ function
Output: Transactions details of a given ID
Step 1: HQ function checks if the given ID exists in blockchain
    if ID exists
        query results ← transaction value of this given ID
    else
        reject the query
End
```

Fig. 3: Architecture of BEC framework

3. VALIDATION AND EVALUATION

3.1 Validation scenario

The roadmap for the validation scenario, which aims to confirm the viability of the smart contract and the authorization workflow, is shown in Figure 5. The AR-01 presents a concern regarding the current window size of a medical block, which is 600*1200mm, although the standard suggests a 900*1200mm window. The problem is then generated, along with a design document, for review. The domain team leader AR-0 reviews the issue detail and approves it with the remark that "this is an issue." The technical engineer (TE-1) notes that this problem cannot be resolved internally and requires the client's additional input. The quality manager (QM-1) approves this issue because it relates to requirements that should be accepted by the client and drawing team. All these permissions are carried out by calling the PE smart contract. Results indicate that every authorization action was carried out automatically and stored in the blockchain. Each transaction records the following information: (1) the user ID executing the action, (2) the judgments (in this case, "approved") made by various users, and (3) the precise remarks made by various parties.

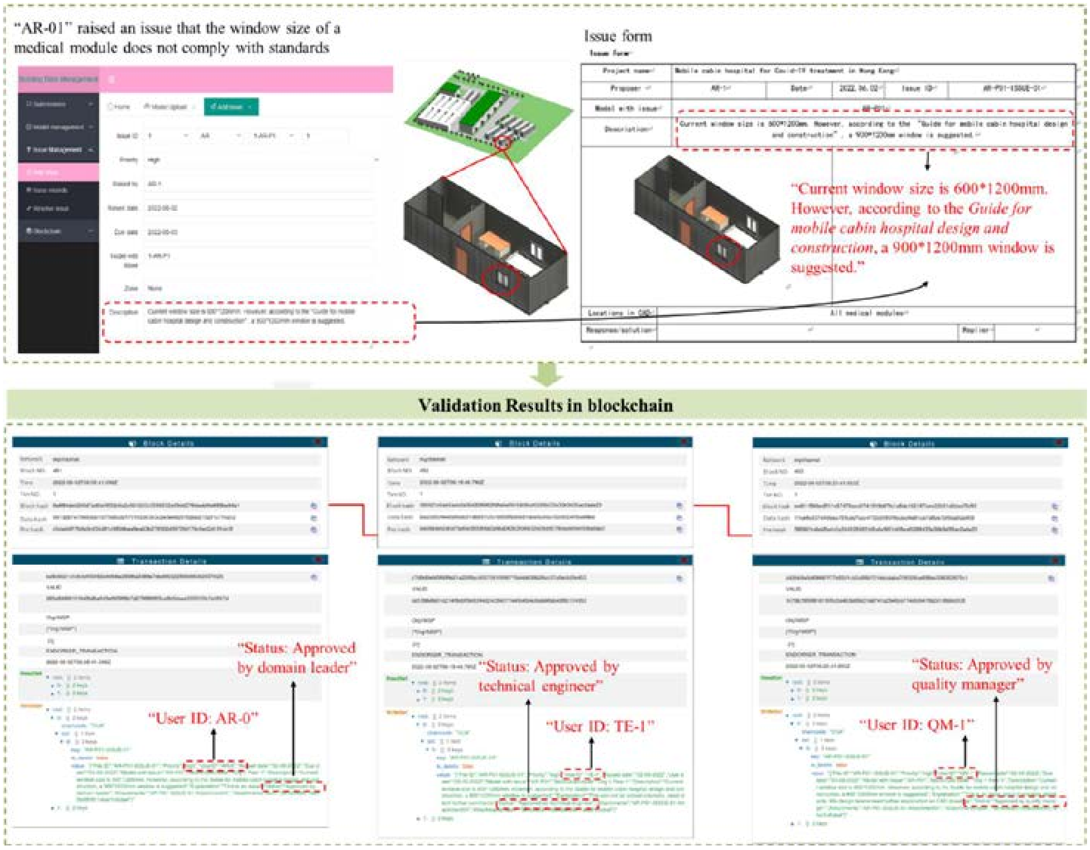

Fig. 5: Framework validation in a BIM permission execution scenario

3.2 Framework evaluation

The evaluation includes two parts. The first is BEC computing performance testing, aiming to see if the proposed framework meets the basic data processing requirements. High latency, like what is in the Bitcoin blockchain, is not acceptable in construction design. The second is a comparison evaluation to test if the BEC framework advances existing BIM solutions regarding design efficiency.

Blockchain latency measures the time required for a smart contract to register a transaction in the blockchain (Ciotta et al., 2021). To determine whether a blockchain's "speed" meets business needs, latency is a crucial statistic in the evaluation process. In MHs where rapid information sharing is required, high latency is problematic. The latency of three smart contracts is measured in this research. To prevent abnormal findings, the repeated test is run ten times. The results in Figure 6 demonstrate that all latency is millisecond-level. No latency standard has been established in construction, because the blockchain is currently being built. Consumers won't notice the delay if the blockchain application's maximum reaction time is less than 1 second, according to Fatokun (2021). Recommendations and best practices from studies (Sheng et al., 2020; Tao et al., 2021) state that millisecond-level blockchain latency is acceptable for design and construction procedures. The BEC framework latency is, therefore, permissible.

The quantitative analysis of how automated smart contracts in the BEC framework could promote efficiency is shown in Figure 7. Three project participants from the MH project—one BIM manager and two designers—were requested to conduct a BIM design coordination case in both the current BIM 360 platform and the prototype based on the BEC framework. Because the BEC framework employs a workflow like current practice, the time investment in the initial model change is the same (30 mins). The model adjustment required the design team to review previous data. The retrieval of a CAD drawing's change history took 11 minutes due to inadequate traceability in traditional solutions. The BIM team only spent 3 minutes identifying all BEC framework traceable blockchain ledger records thanks to the HQ smart contract. Both solutions required P2P collaboration and took 8 minutes. The team leader had to sign a design sheet before it could be pre-revised. The current method required 10 minutes to obtain a physical signature (including the waiting time). In contrast, calling the PE smart contract in BEC took 6 minutes. The BIM team also had to do extra work since they missed a supplier update because they were working on a different system; as a result, they had to spend an additional 10 minutes using existing solutions to fix the problem. Finally, by utilizing BEC and smart contracts (72 min in total), 23% of the time was reduced compared to the current solution (94 mins in total)

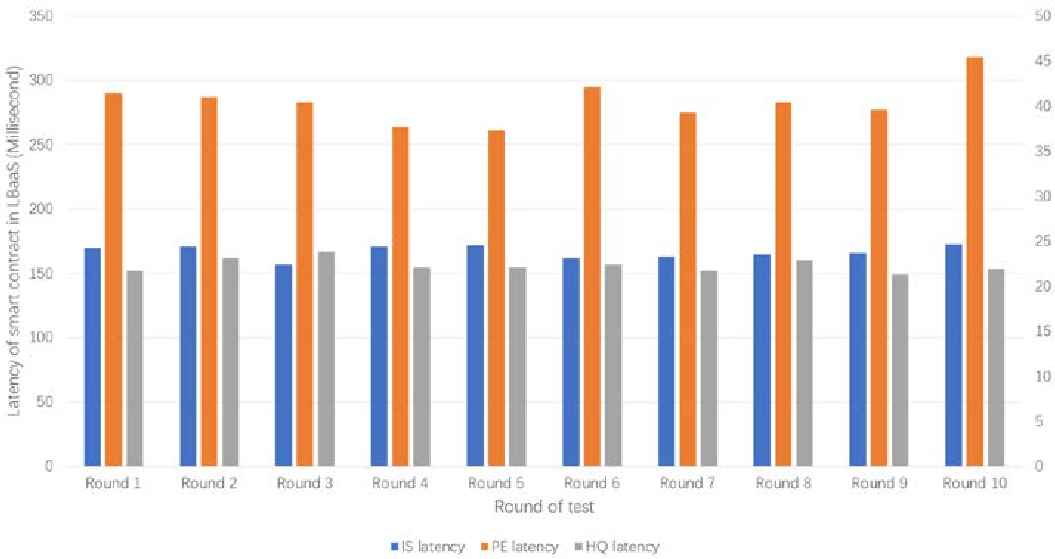

Fig. 6: Latency of BEC framework

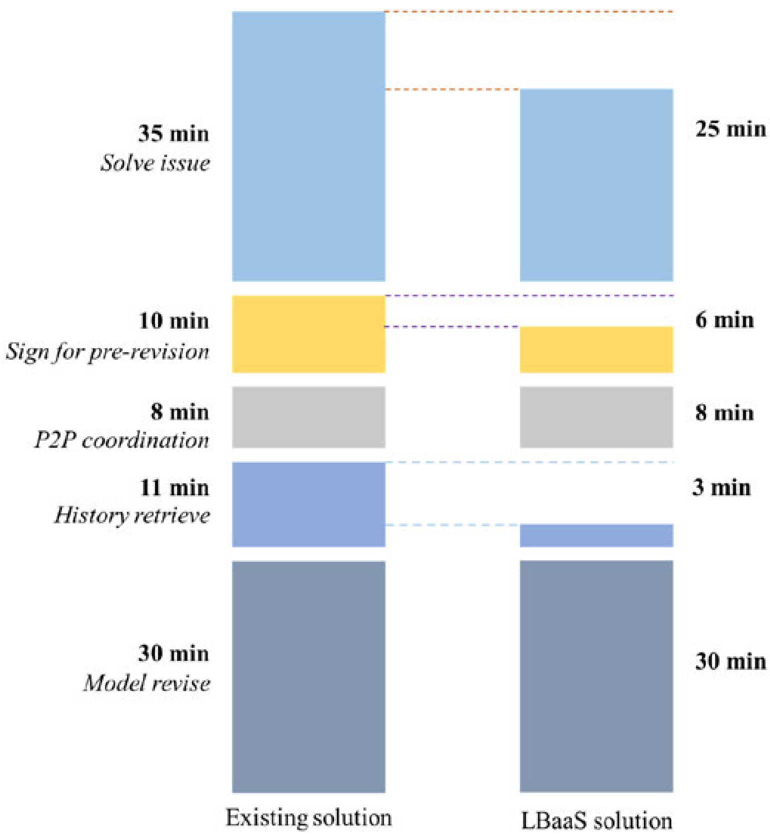

Fig. 7: Comparison results of a BIM coordination scenario

4. CONCLUSION

BIM-based design in MHs risks data security issues that will impair job productivity due to stringent time constraints and complex design processes. Therefore, this study proposes a BEC framework to increase the design efficiency of ECPs while lowering the obstacles to accessing blockchain benefits. Three objectives have been achieved. Firstly, through interviewing BIM participants from an MH project, three risks, namely, lacking transparency, lacking traceability, and lacking permission automation, that will harm the design process are identified. Secondly, a BEC framework is presented to show the technical architecture to guide the data exchange and BEC prototype development. Third, three smart contracts are developed for secure information sharing, permission execution, and historical data query. Due to time and technological limits, there are still restrictions on this early exploration. Non-automatic data verification comes first. The blockchain ledger generates and records data fingerprints. The verification procedure is still manual, though. Further research is still required on automatically comparing a file with its fingerprint.

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INTEGRATING ESG FACTORS INTO CONSTRUCTION PROJECTS: A BLOCKCHAIN-BASED DATA MANAGEMENT APPROACH

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ABSTRACT: *Environmental, Social, and Governance (ESG) investing has become increasingly significant in the Architecture, Engineering, and Construction (AEC) industry. However, the AEC industry faces challenges such as non-uniform standards, complex information sources, and data security concerns when collecting and verifying ESG data. At the same time, as one of the key points of carbon emission in AEC projects, the ESG management of construction projects is still lacking. This paper proposed a blockchain-based ESG data management framework, which designed to address these challenges in the AEC industry. The framework and the smart contract and transaction data model applied in it realize data collection and information verification in construction projects. By leveraging blockchain technology's key features of transparency, immutability, and traceability, the framework ensures secure and efficient ESG data management. Additionally, the InterPlanetary File System (IPFS) technology enables access to original files for data verification and comparison, further enhancing authenticity. By integrating blockchain and IPFS technologies, our proposed solution enhances the reliability and traceability of ESG data in the construction projects, paving the way for more sustainable and transparent practices.*

KEYWORDS: *AEC, Blockchain, Construction Project, ESG, IPFS, Smart contract*

1. INTRODUCTION

Environmental, social, and governance (ESG) investing refers to a set of standards for a company's behavior, which socially conscious investors use to screen potential investments. In the Architecture, Engineering, and Construction (AEC) industry, ESG reporting serves as a method for evaluating a company's contributions to environmental protection, corporate governance, and financial capability. Investors and government management agencies often jointly assess a company's green development prospects based on ESG reports and other indicators. Concurrently, some investment institutions and market participants may establish ESG funds and investment expectations according to the company's ESG score. These behaviors directly influence the company's capital and stock market conditions. However, collecting and verifying ESG-related information is challenging due to various parallel standards, unclear evaluation criteria, and data security concerns. Ensuring that collected data can be safely verified by a third-party organization is also an essential issue since data tampering may render the company's ESG report and score unreliable if all data is controlled by a single department.

Blockchain technology, characterized by high transparency, immutability, traceability, and non-repudiation, is a potential solution for recording transactions and tracking business operations. From cryptocurrencies to smart contracts, blockchain technology demonstrates its potential applications in the construction industry (Turk and Klinc 2017). In the current research, the intelligent construction platform or technology based on blockchain has shown a high degree of usability and advantages. During the construction phase of a building, a large amount of data is exchanged between various departments and personnel. Effective management of these data can improve work efficiency and reduce unnecessary data and economic losses. Features of Blockchain make it conducive to storing and tracing ESG-related data for AEC projects. The construction industry, in particular, plays an important part in global carbon emissions management.

Regarding ESG-related research, the relationship between ESG and corporate performance highlights importance of ESG for business (Zhao, Guo et al. 2018). However, there is currently no available solution for AEC companies with complex information sources and data formats in construction projects. This paper aims to (1) propose a Blockchain-Based ESG Data Management framework, (2) design and apply technical components within the framework, and (3) verify the framework's feasibility through illustrative example. In order to provide a usable ESG data management method in the construction stage.

2. LITERATURE REVIEW

2.1 ESG in AEC Industry

The ESG (Environmental, Social, and Governance) evaluation framework is a multi-level system. The ESG

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Xingbo Gong, Xingyu Tao, Moumita Das, Helen H.L. Kwok, Jack C.P. Cheng, *Integrating ESG Factors into Construction Projects: A Blockchain-Based Data Management Approach,* pp. 327-334, DOI 10.36253/979-12-215-0289-3.31

framework is to measure the ability of enterprises to achieve sustainable development. Since the signing of a series of environmental protection and sustainability-focused documents and conventions, such as the Kyoto Protocol (Protocol 1997) and the Paris Agreement (Agreement 2015), sustainable development has become an increasingly important topic from national to corporate levels. The ESG framework focuses on a company's environmental, social, and governance performance rather than financial performance, helping global investors identify genuinely sustainable businesses.

As climate and environmental issues become more severe, ESG assessment for companies has become a growing trend. The development of ESG-related management has become a focal point for research and disclosure. In 2021, the construction industry emitted approximately 10 billion tons of carbon dioxide, accounting for about 37% of global emissions (Programme 2022). Analysis of carbon emissions management or ESG in the construction industry is important. Related research on ESG and carbon emissions of engineering projects is also in progress, such as carbon emission estimation methods for highway project construction (Liu, Wang et al. 2017), and carbon emission analysis based on BIM in construction stage (Li, Fu et al. 2012).

Popular ESG evaluation frameworks include GRI, ISO and SASB, each with its own set of analytical indicators and disclosure requirements. Certified assessment indicators are accepted by various stock exchanges and can impact the position of a listed company's stock. Research on the impact of ESG on the economic environment and corporate finance (Broadstock, Chan et al. 2021) has proved that ESG has a positive impact on corporate investment and market value. In the practices of ESG integration in AEC projects, some large listed companies have already attempted and explored this approach. For example, companies such as Gensler, China State Corporation, and JLL have carried out ESG analysis and planning. At the same time, industry research also conducted an analysis of the impact of ESG on the construction industry (Daszyńska-Żygadło, Fijałkowska et al. 2022).

However, there are still some challenges for implementing ESG in the AEC industry. The current ESG standards are not uniform, and the information during the construction phase is abundant and complex, making it difficult to apply directly. During the ESG-related management of enterprises, a large amount of business data needs to be submitted to the review unit. Management methods for sensitive data including materials, supplier data, etc. are also not securely secured (Oltsik, J. 2014). Moreover, available statistical standards still need to be constructed. As ESG reporting and rating directly affect the stocks and economic situation of companies, ensuring the reliability of related data has become a difficult issue that needs to be addressed. The ability to ensure the traceability of ESG data still needs further exploration.

2.2 Blockchain in AEC Industry

Blockchain technology is a distributed information system proposed by Satoshi Nakamoto. From its initial development of cryptocurrencies to the current adoption of smart contracts, blockchain technology has been rapidly researched and applied in various fields. Unlike centralized databases, blockchain technology has high transparency, cannot be modified, and is traceable. Its structure is shown in Figure 1. Therefore, while ensuring the characteristics of information security, the application of blockchain technology can provide benefits such as the application of blockchain and Industry 4.0 (Bodkhe, Tanwar et al. 2020), the attempt in the financial system (Treleaven, Brown et al. 2017), etc

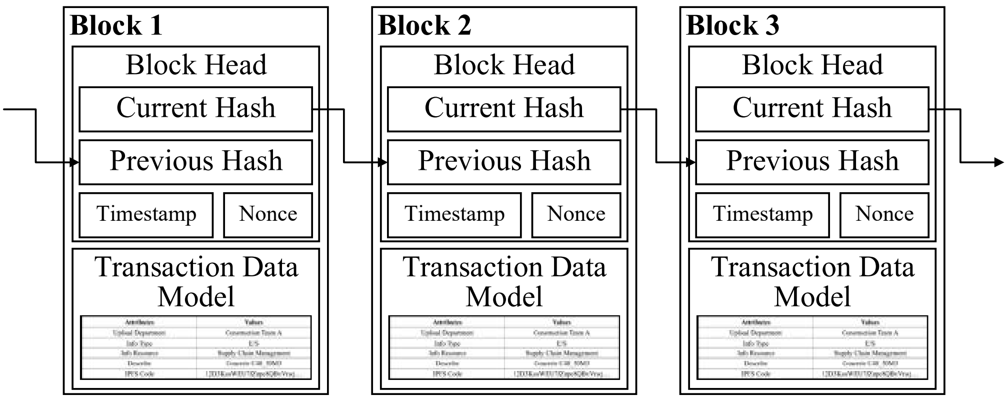

Fig. 1: Structure of Blockchain

In the AEC industry, researchers are exploring the applications of blockchain technology. Examples include a blockchain-based architectural design collaboration framework (Tao, Liu et al. 2022), a blockchain-enhanced BIM (Building Information Modeling) design process integrated with IPFS (Tao, Das et al. 2021), construction project supply chain systems that combine blockchain with IoT (Li, Lu et al. 2022), and a blockchain-based construction quality management platform (Zhong, Wu et al. 2020). These blockchain-based frameworks demonstrate the potential of blockchain technology to enhance the security and interactivity of construction project information, and they contribute to the industry's development of information management capabilities across various domains.

Blockchain systems offer efficient and trustworthy features for smart construction in the AEC industry. In the area of ESG, the requirements for data verification and credibility are high. Due to its high transparency, traceability, and undeniable nature, blockchain technology is a good means of recording ESG data. The potential of blockchain technology in promoting ESG integration, monitoring, and reporting in the AEC industry is worth exploring. In this context, some attempts are already underway, such as research on ESG performance in sustainable supply chains (Liu, Wu et al. 2021), the use of blockchain token designs for ESG reputation to create a more comprehensive carbon trading market (Golding, Yu et al. 2022), and blockchain-based assessment systems using Life Cycle Assessment (Jiang, Gu et al. 2022). However, because the blockchain system cannot store large data. And as a new technology, the technical components and workflow applied in the blockchain system are still lacking. The current research on blockchain technology in ESG management is limited.

3. METHOHOLOGY

3.1 Blockchain-based ESG Data Management Framework

Based on the analysis of the construction process and the sources of ESG data, this paper proposes a blockchain-based ESG data management framework for the construction process, as shown in Figure 2. The framework divides the construction process into three parts: project beginning, construction stage, and project delivery. The information required for ESG collection is placed in the data layer, with specific information sources and types (environmental data or social data) also labeled.

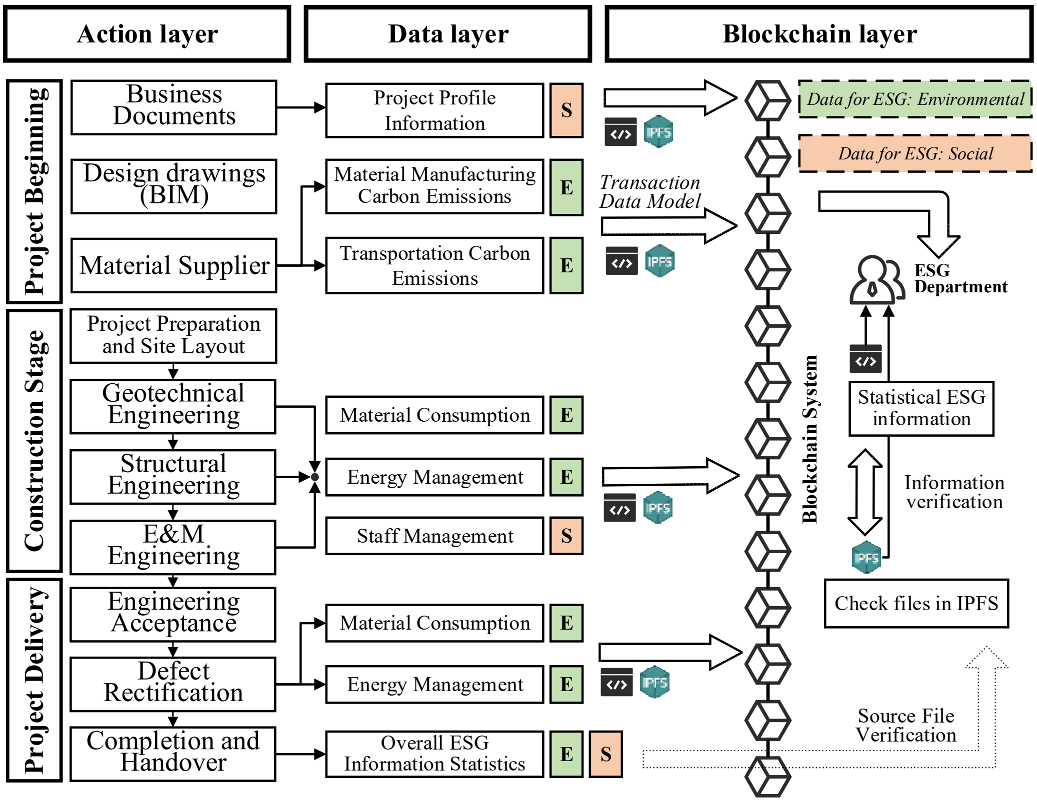

Fig. 2: Blockchain-Based ESG Data Management Framework

The collected information will be uploaded to the blockchain system through the transaction data model. This information includes the identity of the uploader and ESG-related information, and the source files' hash values obtained through the IPFS system are also recorded within the blockchain. When the construction project is completed or the ESG department needs to compile these data, they can access the information within the blockchain system. At the same time, ESG department reviewers can obtain source files through the IPFS system and compare the data in the files with the information in the blockchain to verify the information. Due to the transparency and immutability of the blockchain, all information uploaded to the blockchain system can be properly preserved and traceability is ensured.

3.2 Transaction Data Model for ESG Management

The assessment standards for ESG performance are not uniform, and some exchanges accept ESG assessment scores from multiple institutions for companies. Therefore, this paper has researched several widely recognized ESG assessment standards, compiling their assessment scope and target companies and user groups. Four representative standards include GRI, SASB, ISO, and CDP, as shown in Table 1. Among them, ISO's ESG performance assessment is dispersed across multiple standards, and some NGOs have adopted these standards.

Table 1: ESG Standards and Objects.

Standard	Abbreviation	Scope	Industry	Target	Detailed Name
Global Reporting Initiative	GRI	ESG	Universal	All parties involved	GRI200 GRI300, GRI400
Sustainability Accounting Standards Board	SASB	ESG, Business model	Industry assessment	Investor	SASB Standards
Organization for Standardization	ISO	ESG	Universal	All parties involved	ISO 9001, ISO 26000, ISO 14001, ISO 50001
Carbon Disclosure Project	CDP	Environment	Universal	All parties involved	CDP Standards

Based on the definitions of environmental and social-related information within the collected standards mentioned above, this paper gathers indicators and data sources related to these types of information in construction projects within the AEC industry, as shown in Figure 3. The primary information sources include business documents, BIM (which includes design drawings), supply chain information, and construction site management information. After filtering and processing, this information will affect the ESG reporting and scoring of the construction project.

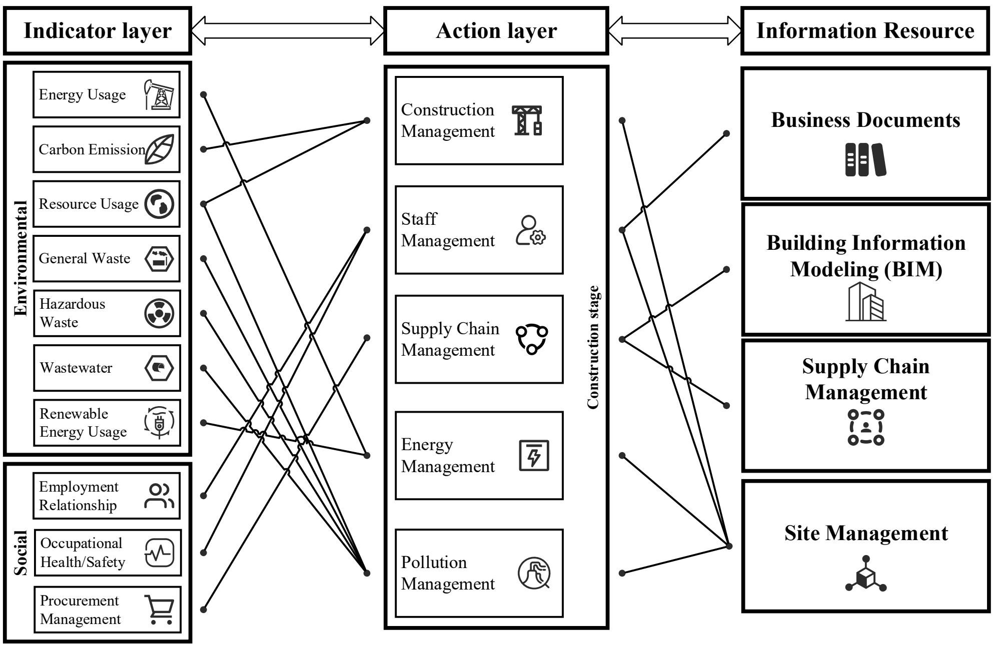

Fig. 3: Sources of ESG Information in Construction Projects

In the blockchain system, both data upload and query need to go through the transaction data model, with the information stored within blocks. A well-designed transaction data model is shown in Table 2. It includes the information uploading department, information type, information source, data description, and IPFS hash code. For instance, when different construction teams upload ESG information, they are required to provide their team identity and specify whether the information is environmental data or social data. For energy usage, the type of energy and consumption can be described; for materials usage, the type and number of materials can be noted; and for personnel management information, descriptions can be provided according to the requirements of the governing department. Once stored in the blockchain system, this information can be provided to the ESG department for analysis and further processing. When needed, the source files can be found in the IPFS system for verification and comparison.

Table 2: Transaction Data Model

Attributes	Values
Upload Department	Construction Team A
Info Type	E/S
Info Resource	Supply Chain Management
Describe	Concrete C40_50M3
Date	20230401
IPFS Code	12D3KooWEU7fZnpc8QBvVrscj…

3.3 ESG-Construction Stage Smart Contract

The blockchain system developed in this paper is based on Hyperledger Fabric. In accordance with the designed transaction data model, this paper presents a smart contract written in the Go programming language, as shown in Figure 4. The smart contract's functions include uploading current information, querying the latest information, and querying all information stored on the blockchain.

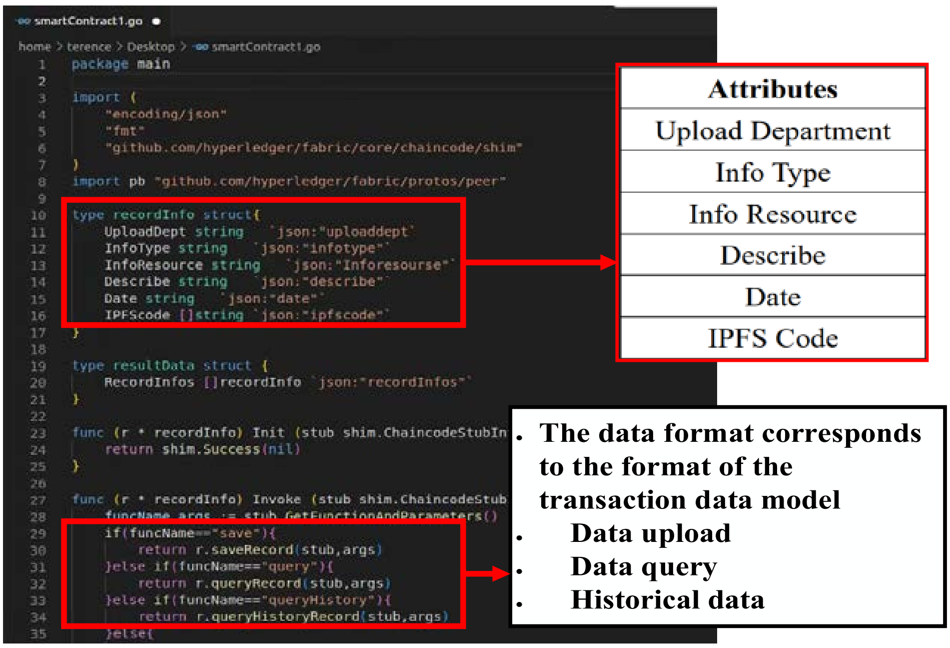

Fig. 4: ESG-Construction Stage Smart Contract

In practical scenarios, the data upload function will be frequently used to ensure real-time updates of ESG data. The other functions of smart contract mainly serve the ESG assessment department. The blockchain-based ESG data management framework consists of two developed technical components: the transaction data model and the smart contract. These two parts support the usage of the framework.

4. ILLUSTRATIVE EXAMPLE

This paper designs two scenarios to test the usability of the blockchain-based ESG data management framework. The first scenario involves data uploading and querying, as this process often needs to be repeated. For example, in actual construction projects, large amounts of materials and energy are used by multiple teams at the same time, and these records are essential in ESG analysis and score. The second scenario involves the ESG analysis department verifying the authenticity of past data. The team can verify the information based on the time information in transaction data model, the timestamps of the blockchain system, and the original files in the IPFS system. These two scenarios serve to validate the usability and traceability, which are characteristics needed by ESG analysis.

4.1 ESG Data Upload and Query

In this paper, the framework is built based on Hyperledger Fabric 2.2. For the first scenario, ESG data is fully stored within the blockchain. The data structure is consistent with the transaction data model settings, and the data query function is also implemented, as shown in Figure 5.

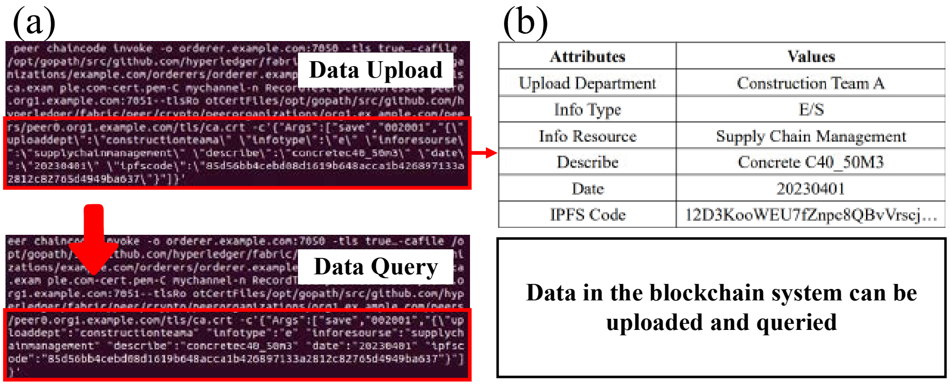

Fig. 5: (a) ESG Data Shows in Blockchain System; (b) Correspondence Between Blockchain System Data and Transaction Data Model;

In this scenario, Construction Team A received 50 cubic meters of C40 concrete from the supply chain management system. Relevant participants were recorded, including the time of the reception event and the IPFS code for the source file (receipt document). The verification results for the upload and query functions of this framework were successful.

4.2 ESG Data Verify

For the second scenario, the verification in this paper utilizes the historical information query function in the smart contract. The results show all submitted ESG-related information. Additionally, by restoring the IPFS code stored in the blockchain and accessing the IPFS system, the experiment retrieves the material receipt document for Construction Site 001 that was stored in the IPFS system during the upload process. The information in the document is consistent with the information stored in the blockchain, as shown in Figure 6.

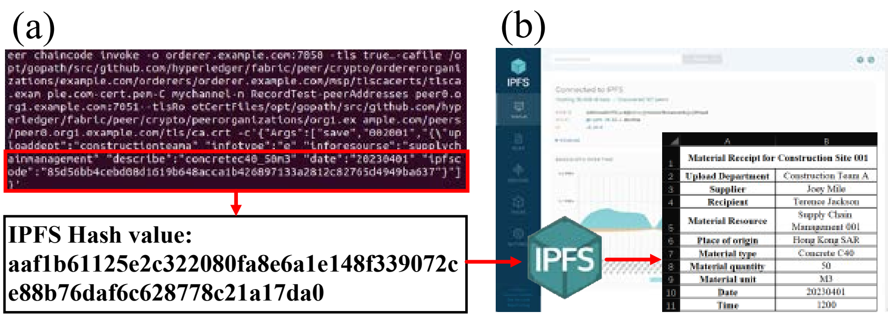

Fig. 6: (a) IPFS Hash Value in Blockchain System; (b) Verification of source files obtained through IPFS;

This experiment demonstrates the successful implementation of the historical information query function in the Blockchain-Based ESG Data Management Framework and its integration with the IPFS system. By providing access to the original files through IPFS, the framework meets the traceability requirements in ESG data management.

5. CONCLUSIONS

In conclusion, the blockchain-based ESG data management framework proposed in this paper effectively addresses the challenges of ESG data collection and verification in the construction project. By leveraging blockchain technology's advantages, such as transparency, immutability, and traceability, the framework ensures the credibility of ESG data while maintaining data security. The integration with IPFS further enhances the data traceability and availability. The verification result of the experiment was also successful.

However, there are still limitations in the research: (1) The framework has only been verified in limited scenarios, and its stability and information throughput capacity have not been tested in actual engineering projects. (2) This design only considers the construction process, and other stages requiring ESG assessment have not been taken into account. In future research, the ESG management process in construction projects should be further considered, while further reducing the cost and efficiency of ESG assessment through secure information technology. As carbon neutrality goals are established and the demand for low carbon solutions becomes increasingly urgent within the AEC industry, further exploration of ESG analysis and technological applications is still needed.

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A BLOCKCHAIN-BASED SECURE SUBMISSION MANAGEMENT FRAMEWORK FOR DESIGN AND CONSTRUCTION PHASES

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ABSTRACT: *AEC projects generate numerous versions of BIM models during the design and construction phases. This process is complicated by the sheer number of domains in large projects and the interlinkage of BIM deliverables (for example the structural BIM model follows the corresponding architectural BIM model). However, due to the generation of multiple versions and parallel design progress in different domains (especially in large projects), multi-domain delivery teams often fail to access and comply with the latest/required/approved design requirements during the progression of the design phase and complete issue addressing during the construction phase, which creates confusion, may lead to disputes. Moreover, due to the contractual nature of the parties involved data and process security is also very important. Therefore, this research presents blockchain-based secure coordination workflows for effective collaboration, parallel design progress, and issue management among BIM developers from multiple domains. Smart contract logic for facilitating dynamic dependency logic for coordinating linked multi-domain submission over the project timeline is presented. A method to ensure that issues are completely, and timely addressed, and related parties are held accountable for their actions or non-response is presented by integrating a BIM change identifier and blockchain in typical issue management workflows. The method considers collaborative design and issue management workflows for the secure, efficient, and complete design of BIM models. The method is validated using an ongoing large construction project in Hong Kong.*

KEYWORDS: *Version Management, Issue Management, Security, Blockchain.*

1. INTRODUCTION

Construction projects generate huge amounts of digital information that requires sharing among stakeholders from different construction domains during the design, construction, and operation phases. It is well established that effective building data management strategies (including rules, programs, and practices) integrated with a Common Data Environment (CDE) is recommended to streamline coordination among project partners to ensure project success. However, the existing CDEs are faced with several error-inducing methods/gaps that cannot prevent incomplete BIM model delivery during the design and construction phases or hold the responsible stakeholders accountable for their actions. In particular, the first problem in existing CDEs is the lack of secure (in terms of accountability) and automated coordination methods in multi-domain delivery teams – Construction projects especially during the design phase generate a large number of BIM model versions. This process is complicated by a large number of domains in large projects and their interlinkage in submission management. For example, it is a regular practice to design structural models (the dependent model in this case) based on the latest or approved architectural model (the leading model in this case). Similarly, MEP (Mechanical, Electrical, and Plumbing) models are designed based on both architectural and structural models. However, due to parallel design progress that creates multiple versions in each domain, multi-domain delivery teams often fail to access and comply with the latest/required/approved design requirements during the progression of the design phase which creates confusion, causing incomplete deliveries and resulting in disputes between the delivery teams. Therefore, methods to facilitate automated coordination of multi-domain submission management and ensure accountability of delivery teams are necessary. The second problem in existing CDEs is the lack of methods to automatically check the completeness of BIM deliverables and to ensure accountability of stakeholder actions during the construction phase. The construction phase is more complex in comparison to the design phase due to the involvement of real-time data, time-bound tasks, and the addition of new stakeholders such as sub-contractors from multiple domains. In big projects, a large number of issues may be generated for reviewing, resolution, and approval by multiple stakeholders. Hence integrating automatic delivery completeness checker and stakeholder accountability in the traditional issue management workflow is desirable. Some existing CDEs facilitate issue resolution workflows with options for manual coordination. However, this may not be efficient in large projects involving hundreds of issues and stakeholders. In addition, the existing CDEs lack robust and secure methods to ensure stakeholder accountability.

A BIM-based issue management approach that incorporates the integration of issue management with other BIM processes such as design coordination was proposed (Wang & Wang, 2020). Jaly-Zada et al. (2015) extended the IFC schema to record a history of changes. A graph-based approach (Moayeri et al., 2017) was investigated to

Referee List (DOI: 10.36253/fup_referee_list)
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Moumita Das, Xingyu Tao, Yuxing Xu, Jack C. P. Cheng, *A Blockchain-Based Secure Submission Management Framework for Design and Construction Phases,* pp. 335-342, DOI 10.36253/979-12-215-0289-3.32

capture the ripple effects of BIM version change. Jiao et al. (2013) developed a version update identifier at a BIM-object level to track changes and assign accountability for version change. Commercial and open-source applications such as Autodesk BIM 360 (Autodesk), Newforma BIM Track (Newforma, 2021), and Kubus IFC viewer (Kubus, 2022) have also deployed version and issue management for BIM deliverables. However, the existing approaches lack methods to accommodate submission dependency and completeness-related requirements in the traditional version management and issue management workflows.

Therefore, a "Blockchain-based Secure Submission Management Framework" is presented that captures information from Open BIM models using the IFC format, documents, stakeholder actions, and automated methods and integrates them with blockchain to facilitate stakeholder accountability. The framework includes – (1) a Blockchain-based Dynamic Dependency Workflow to facilitate coordination and stakeholder accountability in large projects with dynamic interlinkage among submissions from different domains and (2) a Blockchain-based Completeness Checking Issue Management Workflow to facilitate automatic checking for faster/efficient issue resolution. To realize this framework, the existing IFC schema was extended to include version and issue-related information. An entity to store blockchain transactions was also created in the extended IFC schema to integrate IFC models with block-chained information. Blockchain smart contracts and ledger data models were developed to irreversibly record stakeholder actions during the version management and issue management phases. An efficient BIM change identifier method was developed using the BIM-segmentation and hashing method to efficiently parse and identify changes between two BIM models. This method was integrated into the traditional issue management workflow to automatically check whether all the issues related to a BIM deliverable were addressed or not. A prototype for the proposed framework was developed using the Hyperledger Blockchain Platform (Hyperledger, 2020) and was tested in an ongoing project in Hong Kong.

The remainder of this paper is organized as follows: Section 2 presents the methodology of the proposed framework. The framework validation scenario and results are discussed in Section 3. The paper is concluded in Section 4.

2. METHODOLOGY

This section describes the methodology used to facilitate secure versioning and issue management in construction projects. As shown in Figure 1, the framework consists of three modules – (1) version management module and (2) issue management module that connects to a blockchain layer. These modules are discussed as follows:

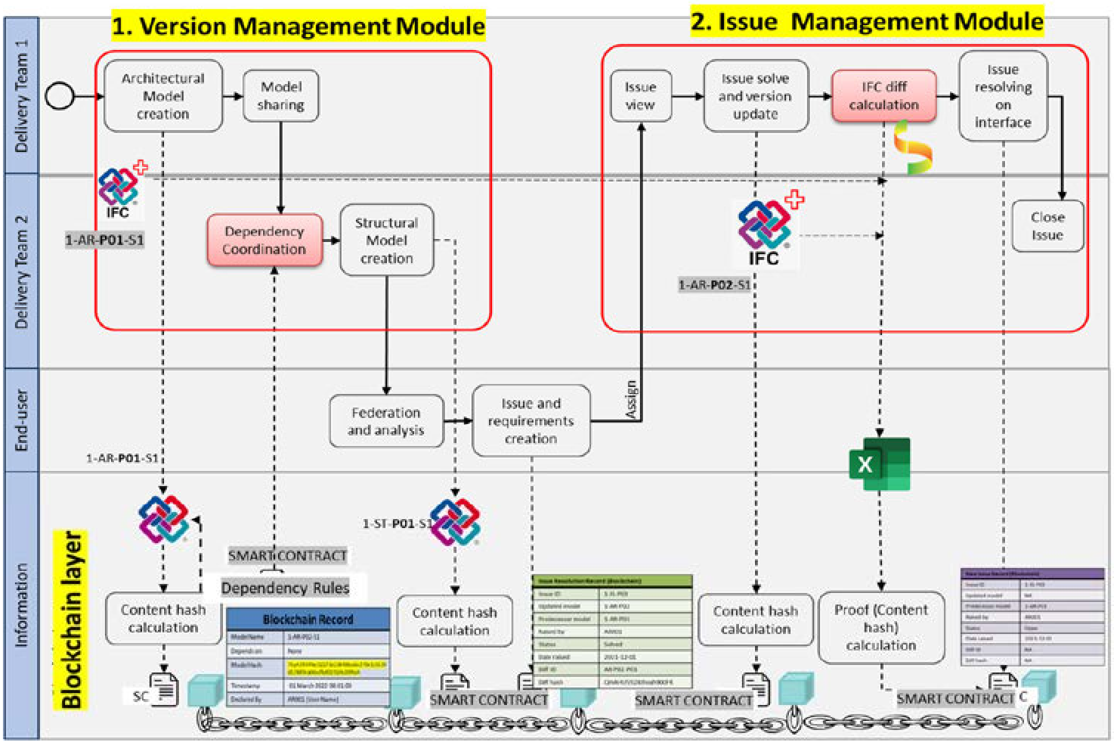


Figure 1 Methodology using Open BIM (IFC) for secure, complete, and coordinated Submission Management

2.1 Blockchain-based Version Management Module

This module manages and coordinates submission management considering versions and dependencies from different domains in an AEC project. AEC project submissions have dependencies on each other. For example, the submissions from the MEP (Mechanical, Electrical, and Plumbing) domain are dependent on the structural and architectural model of a building in general. This means the delivery team of the MEP model should ensure that they are using the latest/approved version of the architectural and structural models. Figure 2 shows some examples of dependency rules identified from a large ongoing project in Hong Kong. However, due to many versions generated during the design phase in each domain, the project stakeholders often fail to follow the latest/approved/assigned versions of the leading models. In this case, a dispute may happen between the leading and the dependent delivery teams causing a delay to the entire project schedule. Therefore, a method including IFC extension and smart contract logic was created to ensure that the dependent parties download the latest/approved/assigned leading model before they can submit their own models. Along with this checking, this action is also recorded in the blockchain to facilitate accountability of the leading and dependent parties at a later stage. Figure 3 shows the extended IFC schema which stores information such as Model name (includes domain name) and version number. An entity to store a blockchain transaction is also added in the extended IFC, called "TnxID" as shown in Figure 3, to link IFC models with blockchain ledgers.

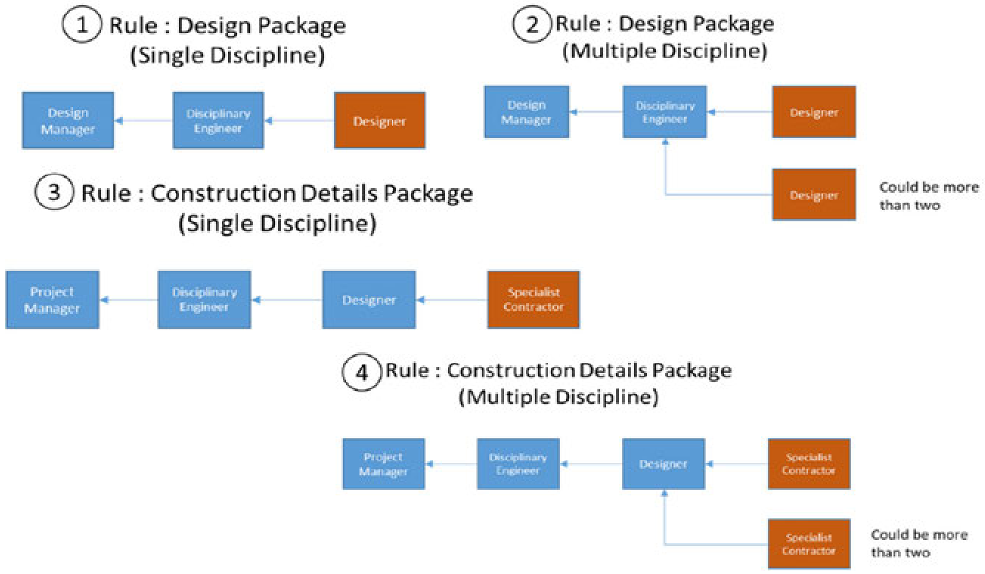


Figure 2 Example of submission dependency rules in AEC projects

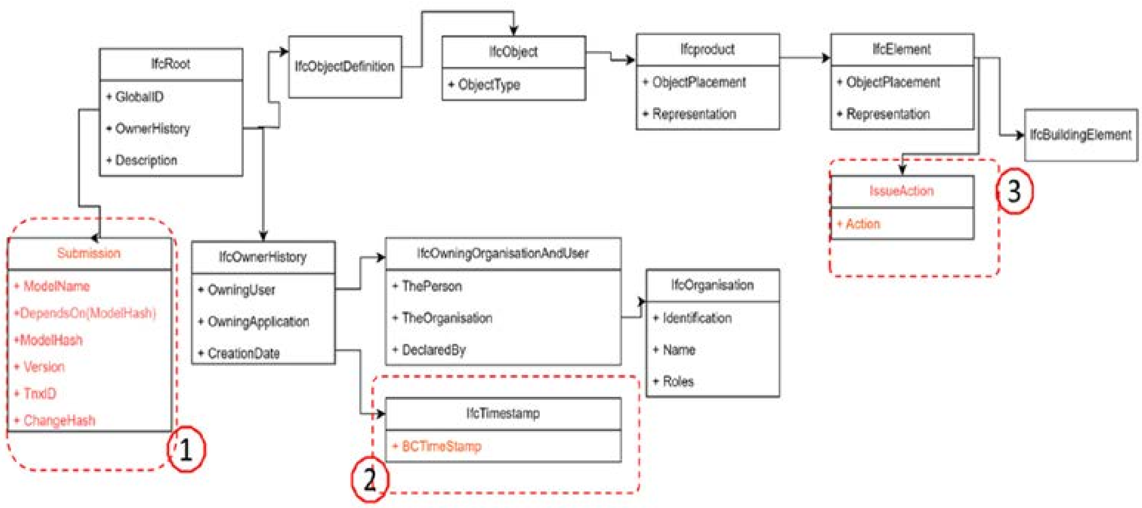


Figure 3 Extended IFC Schema for submission Management

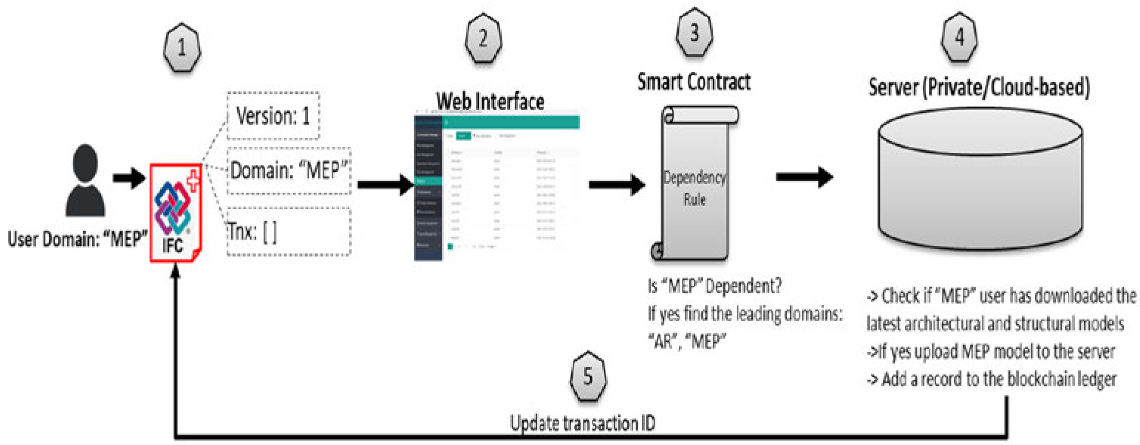


Figure 4 Methodology for Dependency Checking by the Version Management Module

As shown in Figure 4, dependency checking is performed by the version management module in four steps – (1) populating the IFC to be submitted with information such as version number and domain name, (2) submitting via a web interface, (3) invoking blockchain smart contract containing the dependency rule, (4) checking if the corresponding leading models were downloaded, (5) adding a record to blockchain ledger (Figure 5 (a)) and updating the uploaded model with a transaction ID.

Version Record	
Model Name	1-MEP-P02-S1
Depends on	1-AR-P02-S1
Model Hash	76yh39444ec32273e238400ce6c270e1c5539d17889ca065cfbd0191d6209huh
Timestamp	01 March 2022 08:01:00
Declared By	MEP001 (User Name)

(a)

Issue Resolution Record	
Issue ID	1-IS-P03
Updated model	1-AR-P02
Predecessor model	1-AR-P01
Raised by	AR001
Status	Solved
Date raised	2021-12-01
Diff ID	AR-P02-P01
Diff hash	QmAHU5928Jhuyh900FR

(b)

New Issue Record	
Issue ID	1-IS-P03
Updated model	NA
Predecessor model	1-AR-P01
Raised by	AR001
Status	Open
Date raised	2021-12-01
Diff ID	NA
Diff hash	NA

(c)

Figure 5 Blockchain Data Models for Version Management and Issue Management

2.2 Blockchain-based Issue Management Module

As shown in Figure 1, a workflow was developed to integrate issue management logic with OpenBIM and Blockchain to ensure issue resolution completeness and accountability. This workflow links project issues, stakeholders (Responsible, Accountable, Consulted, and Informed Parties), IFC-based change identifiers in BIM models, and blockchain.

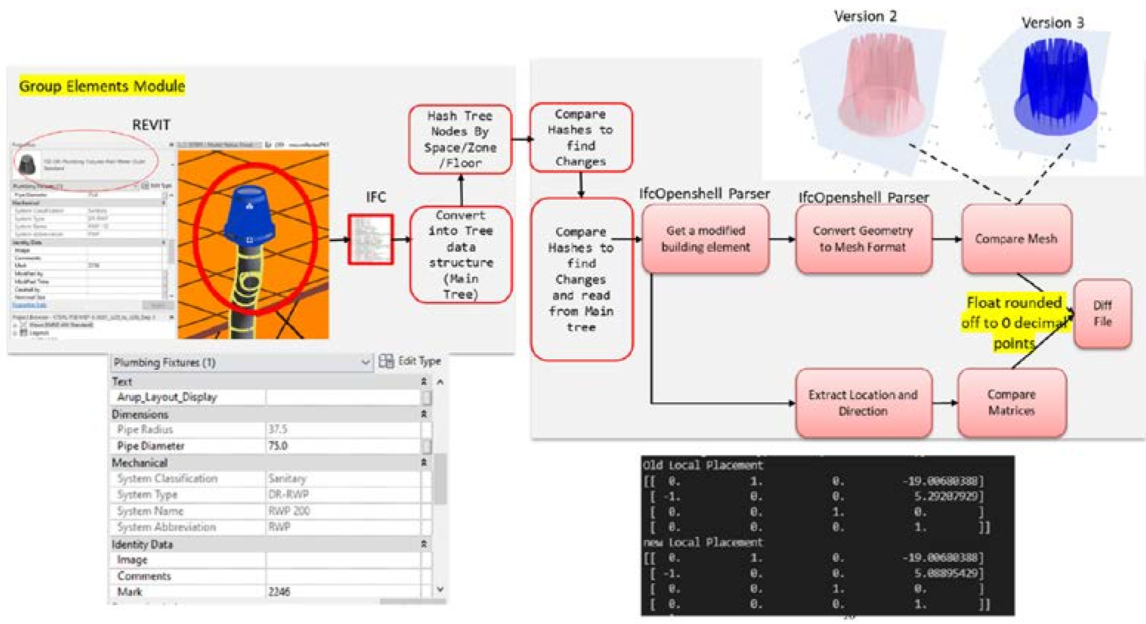


Figure 6 Methodology of the BIM Change Identifier (Diff) Module using OpenBIM and Hash-based Segmenting.

As shown in Figure 1, a BIM change identifier (called Ifcdiff module) is developed and integrated in the issue management workflow, OpenBIM has been used to integrate (interoperability properties) a BIM model change identifier (Diff) and blockchain with a traditional issue management workflow. Figure 4 shows the methodology of the diff which involves – (a) parsing the IFC models, (b) converting it into a tree-like data structure (using OpenShell)-called the main tree, (c) compressing the tree element-wise, space-wise, and zone-wise (as per user input) into a hash-based tree data structure, (d) comparing between BIM versions using the hash-based tree and identifying differences between hashes, (e) extracting the details of the changed elements for fine-grained comparison for geometry, location, and properties, (f) converting element shapes into a mesh data structure and perform mesh comparison to identify the change in geometry, (g) compare location and direction matrices to identify changes in the position of elements, (h) excel-based report generation recording the changes (addition, deletion, and modification based on IFC guides) for manual and automated review, and (i) recording of proof the diff file and issue status on the blockchain (as shown in Figure 5(b)).

The workflow facilitates automated checking of issue resolution using the openBIM-based Diff logic. End users such as issue creators can mark the building elements (using IFC *Global IDs*) (using the IFC extension as shown in Figure 3), which are to be added/modified/deleted as per the issue resolution process. The workflow automatically updates the issue status as incomplete if all the issues are not resolved and send a notification to the issue creator for manual review and override if desired. As shown in Figure 1, the issue creation and resolution are recorded on the blockchain for accountability.

3. VALIDATION

For validation a prototype was A prototype was developed and tested. Python and Openshell (IfcOpenShell, 2022) are used to develop the diff algorithm, which is used to detect model changes that should be tracked and blockchained. Hyperledger Fabric serves as the blockchain platform to immutably and traceably record BIM coordination, delivery, and operation actions. This platform provides a secure and scalable way to manage BIM data, enabling efficient collaboration between different stakeholders. It also provides a transparent and secure way to manage BIM data, ensuring that project progress is monitored and tracked effectively.

The dynamic dependency logic and the blockchain interface and tested for versioning in the Kai Tak Sports Park (KTSP) Project. The project has over 40 domains up to March 2023 which created at an average of 200-300 versions per fortnight from the entire project. This required complex dynamic rule generation for linking submissions and managing their versioning. The prototype was tested and found to be effective in the management of multi-domain submission management for the KTSP project. The end users found the platform to have the following value additions – (a) team members are sure about the model status (because of blockchained single source of truth), (b) team members are sure if the submissions have followed the correct dependency and version for model delivery for a milestone/review, (c) accountability of delivery teams to prepare deliverable with the correct information is added.

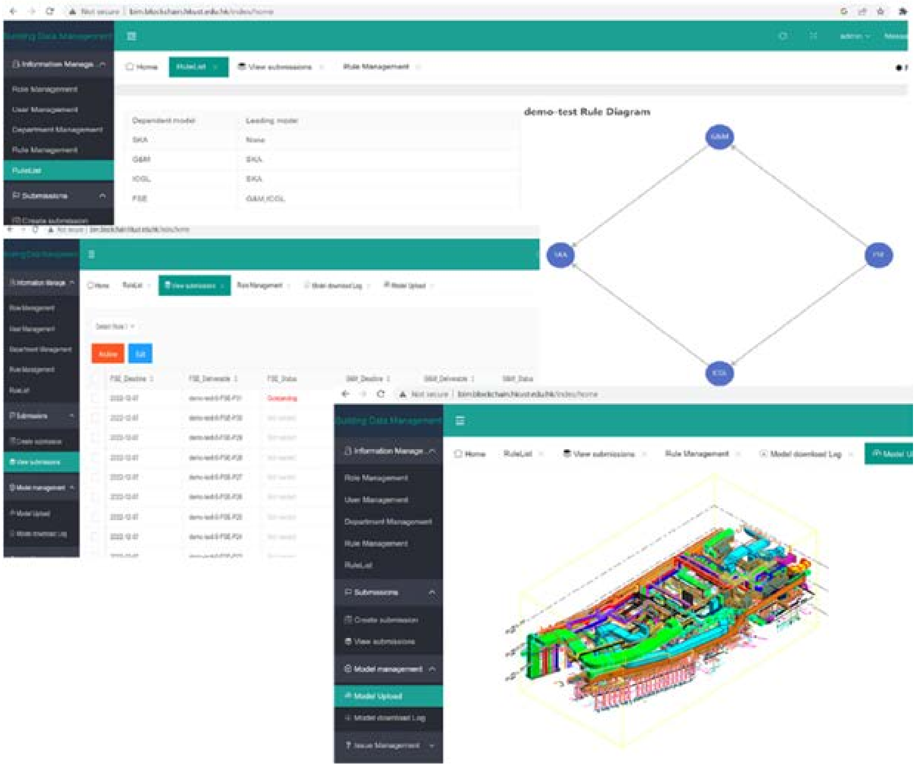
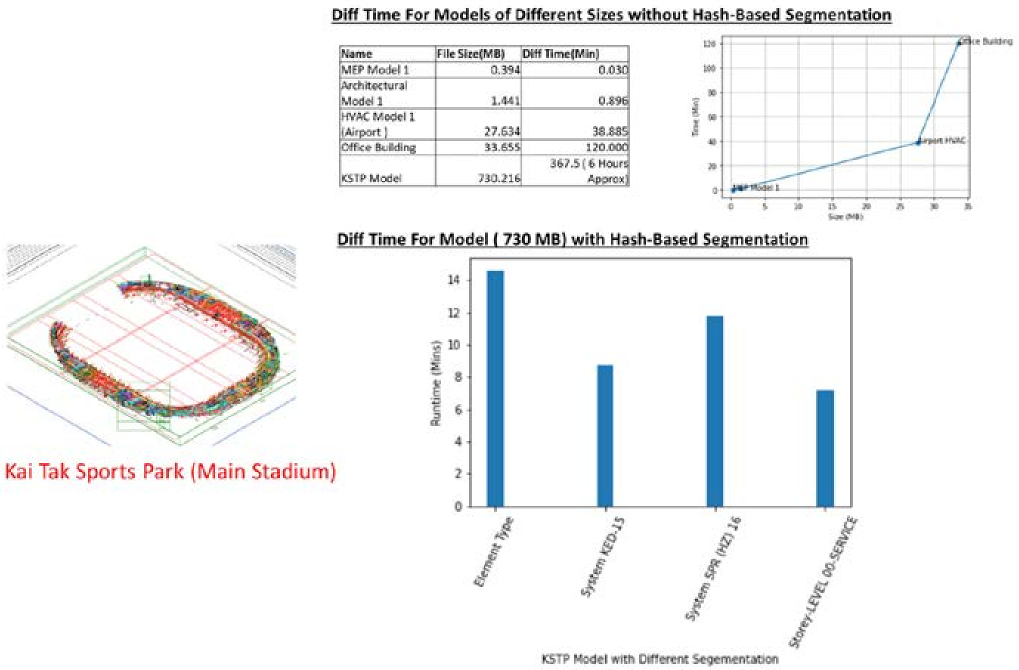


Figure 7 Prototype Web-interface Showing Dynamic Rule Creation and BIM Visualisation

Figure 8 shows that the BIM change identifier was evaluated on models ranging from sizes 0.3 MB to 730 MB. It can be seen that there is a linear rise in the computation time of the diff program with increasing file size. As described in the methodology section, the diff logic uses a hash-tree-based data structure that segments the BIM model and facilitates comparison for a faster computation time. Figure 8 shows the results of hash-tree based segmentation on a model sized 730 GB. This method is particularly efficient in identifying small changes (such as a few modifications on a particular element type or floor) in large BIM models. The prototype is also being tested on the ongoing KTSP project. The end users have so far evaluated the platform as – the actions of all parties are blockchained which will be useful to hold parties accountable if the need arises. They have also stated that a confident audit trail record will be created, that will help resolution of future disputes or remeasurement of works upon quantifying and monetizing additional works variations.



Name	File Size(MB)	Diff Time(Min)
MEP Model 1	0.394	0.030
Architectural Model 1	1.441	0.896
HVAC Model 1 (Airport)	27.634	38.885
Office Building	33.655	120.000
KSTP Model	730.216	367.5 (6 Hours Approx)

Figure 8 Validation of the Diff Module of the Issue Management Workflow

4. CONCLUSION

A blockchain-based framework for version and issue management was presented in this paper. With the advent of digitization and the inherent contractual organizational structure in the construction industry, data security, integration, and stakeholder accountability has become very important. This is more important, especially in BIM projects which contain sensitive information and are difficult to manage in a multi-data owner environment. Therefore, the proposed framework includes - (1) Blockchain-based Dynamic Dependency Workflow and (2) Blockchain-based Completeness Checking Issue Management Workflow to facilitate integration and accountability in large-scale construction projects. For validation, a prototype was developed and implemented on an ongoing Hong Kong based project with real end users. The framework was found useful in terms of security and functionality by the end users including representing a single source of truth, maintaining version dependency, and completing outstanding issues.

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ZERO-KNOWLEDGE PROOF FOR TRUSTED CONSTRUCTION MANAGEMENT: A PRELIMINARY STUDY OF ADAPTIVE BLOCKCHAIN BIM IDENTITY AUTHENTICATION

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ABSTRACT: *Blockchain technology emphasizes trust and collaboration through distributed networks and is deemed to contribute to building information modeling (BIM) based construction collaboration and management. However, the open nature of blockchain introduces severe cybersecurity attacks that undermine the trustworthiness of construction management. One salient point is identity authentication for security BIM data access in the blockchain environment. The traditional public-private key or password authenticate methods are vulnerable to malicious theft. Zero-Knowledge Proof (ZKP) is an emerging, password-free method for authenticating identities. It allows one party to prove the truth or falsity of a statement to another party without revealing any meaningful information to the counterpart. Therefore, this study proposes a preliminary user authentication protocol based on the non-interactive ZKP protocol, specifically the zk-SNARK protocol, for adaptive authentication of blockchain BIM. The adaptive authentication recognizes a random subset of on-chain historical BIM operation records to prove the identity according to the protocol. Without revealing any meaningful knowledge to the authentication system, this adaptive data access control prevents password attacks using the BIM records on-chain. Finally, the proposed protocol is deployed on the test blockchain and implemented in a preliminary case study to illustrate the feasibility and effectiveness of the proposed method. The main contribution of this paper is twofold. Firstly, the theoretical contribution is proposing a novel zk-SARKs-based identity authentication protocol that utilizes the on-chain BIM operation records. Secondly, the practical contribution relies on presenting a ZoKrates-based workflow of generating proofs, creating smart contracts, and deploying on the blockchain for verification.*

KEYWORDS: *Zero-knowledge proof, Blockchain, BIM, Construction Management, Identity Authentication.*

1. INTRODUCTION

In multi-party construction activities, collaboration and trust emerge as significant yet intricate issues. Building Information Modeling (BIM) stands as a trending and burgeoning technology within the construction industry, facilitating efficient cross-disciplinary collaboration among stakeholders. However, given the inherent characteristics of construction activities—encompassing multiple data contributors, consumers, and geographically dispersed stakeholders—the centralized, file-based BIM collaboration necessitates stringent data access control. This measure is crucial to prevent deliberate cybersecurity attacks, such as login attacks.

Ensuring that the right individuals access the appropriate BIM content – in essence, addressing authentication concerns – has emerged as one of the most critical issues in BIM-based collaboration. For example, Skandhakumar et al. (2018) proposed a BIM-based security model presented by BIM-XACML language to facilitate conditional access to BIM, and Zheng et al. (2019) offered a new context-aware access control model for the decentralized cloud BIM system. These studies cannot avoid password attacks, which represent intentional attacks to steal the authentication credentials such as passwords and private keys.

Blockchain technology brings a transformative alteration from centralized BIM to distributed BIM that is deemed to achieve transparent, traceable, and consensus-based trusted collaboration with better encryption and security (Subangan & Senthooran 2019; Nawari & Ravindran 2019). Blockchain is a distributed ledger network first proposed in 2008 and implemented in 2009 (Zheng et al. 2018). In recent years, the integration of BIM and blockchain has been studied extensively, especially in the data security aspects. Inappropriate distribution and excessive BIM transparency may lead to a loss of reputation and trust.

Considerable literature on trust has grown up around the theme of blockchain BIM in different project aspects (Wu, et al., 2022; Zhao, Chen, & Xue, 2023). For example, Das et al. (2021) categorized BIM data security into five types and emphasized the confidentiality and authenticity of distributed BIM. The confidentiality of BIM represents the necessity of safe data access by authorized people or organizations, and authenticity involves user-related and data-related regions. The Hyperledger community presented a "privacy data" mechanism that only stores the sensitive data as hash code in ledgers and source data such as BIM files off-chain (Androulaki et al. 2018). Accordingly, Tao et al. proposed an access control model based on asymmetric encryption and sensitive BIM model components decomposition (Tao et al. 2022). Much previous research utilized traditional encryption

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Lingming Kong, Rui Zhao, Fan Xue, Zero-Knowledge Proof for Trusted Construction Management: A Preliminary Study of Adaptive Blockchain BIM Identity Authentication, pp. 343-351, DOI 10.36253/979-12-215-0289-3.33

or access control policy to guarantee secure data access in the distributed blockchain environment, which encountered the same challenge as the centralized BIM, password attacks.

Adaptive authentication stands as a potential solution for circumventing password attacks. Zero-knowledge proof (ZKP) constitutes a cryptographic technique that empowers the prover to persuade the verifier without divulging further meaningful information regarding statements. ZKP has three significant properties: (1) completeness. If the statement or witness is true, the verifier can be convinced by the honest prover. (2) reliability. The prover can deceive the verifier with a negligible probability if they do not know the statement. (3) zero knowledge. The verifier only obtains the information "the prover has this knowledge" without extra meaningful information (Goldreich & Oren 1994). These three main properties of ZKP are deemed to contribute to multi-party identity authentication for blockchain BIM. Typically, ZKP can be classified into two types, interactive ZKP and non-interactive ZKP (Hu et al. 2018). The non-interactive ZKP is widely used in the blockchain environment due to its one-way communication between the prover and the verifier, specifically the zero-knowledge Succinct Non-interactive ARguments of Knowledge (zk-SNARKs) protocol (Parno et al. 2016; Groth 2016). Anonymous currencies such as Zerocash (Sasson et al. 2014) and SERO use zk-SNARK in the blockchain domain for implementing privacy transactions. A large volume of published studies describes the role of ZKP in solving identity authentication problems of blockchain. Wang et al. (2020) summarized the existing solutions to privacy protection issues in blockchain and emphasized the effectiveness of ZKP. Yang et al. (2020) formulated an identity management scheme by leveraging smart contract and ZKP algorithms; Sun et al. (2021) proposed a two-part framework of ZKP in blockchain as on-chain and off-chain parts respectively, aiming to provide a solution of security private data access in the blockchain environment. However, due to the high cost of computation and storage of ZKP, the lack of using historical data stored in the blockchain, and the primitive application of blockchain BIM, research on ZKP-based identity authentication for BIM collaboration in the blockchain environment is still preliminary.

For a construction project, both BIM files and BIM-related operation records are stored in the blockchain system. Due to the limited storage capability of blockchain and the massive-volume nature of BIM files, a typical blockchain BIM system is composed of two parts: on-chain and off-chain parts. The on-chain part stores the metadata of BIM files, including the file name, size, owners, creating time, version information, operation records, and other file-related descriptive data. The off-chain part keeps large-size BIM data such as BIM model files and documents of the project. A representative two-part structure blockchain BIM system is proposed by Tao et al. (2021), and Xue and Lu (2020) introduced a semantic differential approach to capture changes in the local BIM model as transactions on chain. The storage methods of BIM data in the blockchain are out of the scope of this paper, but the BIM data itself is possible to facilitate the ZKP-backed identity authentication of the construction blockchain.

This study proposes a Zk-SNARKs-based identity authentication protocol for blockchain-backed BIM collaboration. By utilizing the random subset of historical data records in the blockchain, stakeholders involved in the construction projects with distinct roles and responsibilities access the blockchain channel through an adaptive authentication process. By leveraging ZKP, a dynamic login function is achieved that avoids password attacks and provides a trusted identity authentication function. The proposed Zk-SNARKs-based BIM user authentication protocol is described in part 2, and a case pilot is illustrated to prove the possible feasibility of the protocol in part 3. Then, the pros and cons of the protocol are discussed in part 4, and part 5 shows the limitations and future works.

2. A ZKP-BASED AUTHENTICATION PROTOCOL FOR BLOCKCHAIN BIM

The two-step authentication processes between BIM stakeholders and the blockchain network is shown in Fig. 1. Firstly, the BIM stakeholders act as provers to prove their authority to the blockchain by providing statements, which are the knowledge of BIM in their mind. Then, the blockchain verifies the correctness of the statement automatically by the deployed smart contract and responds to the BIM stakeholder.

2.1 The zk-SNARKs-based authentication protocol

The structure of the proposed zero-knowledge Succinct Non-interactive ARguments of Knowledge (zk-SNARKs) based authentication protocol is depicted in Fig. 2. The first layer is the blockchain layer which is composed of a block network to store the BIM editing records. On top of the blockchain layer, various smart contracts deployed on the blockchain constitute the second layer. Three types of smart contracts for data storage, data querying, and proof verification are involved. With these smart contracts, BIM stakeholders can interact with the blockchain network, such as uploading the BIM editing records by the data storage smart contract and verifying their identities by the verifying smart contract. The uppermost layer is the application layer, which provides functions for users to interact with the blockchain. Two services, namely identity provider (IdP) and BIM server provider (BIMSP), are designed in this layer. The IdP are various identities, including project manager, civil engineer, designer, BIM engineer, and their combinations. IdP is designed to provide multiple options for users' identification. The BIMSP provides adding, modifying, deleting, and querying operating authorities of BIM models. Authorized users can get editing rights corresponding to their identity in the BIM model.

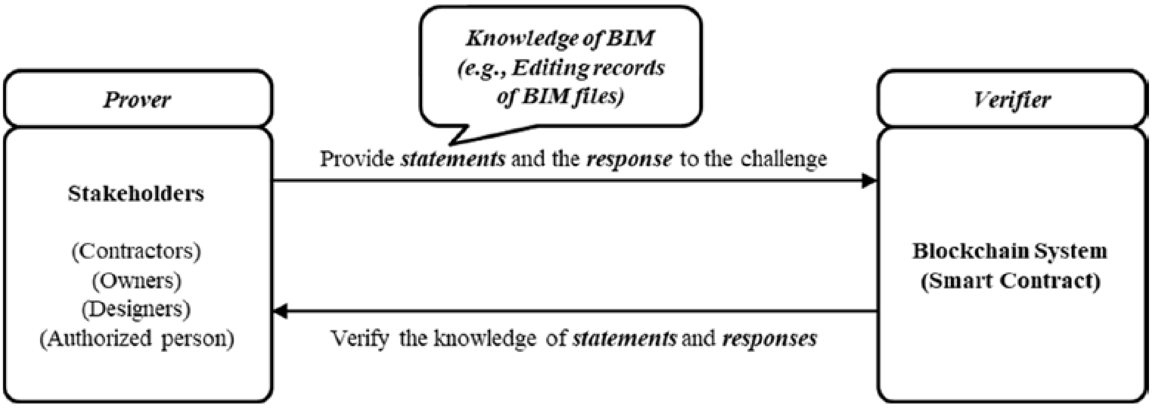


Fig. 1: Possible facilitation of BIM in the structure of ZKP for construction blockchain

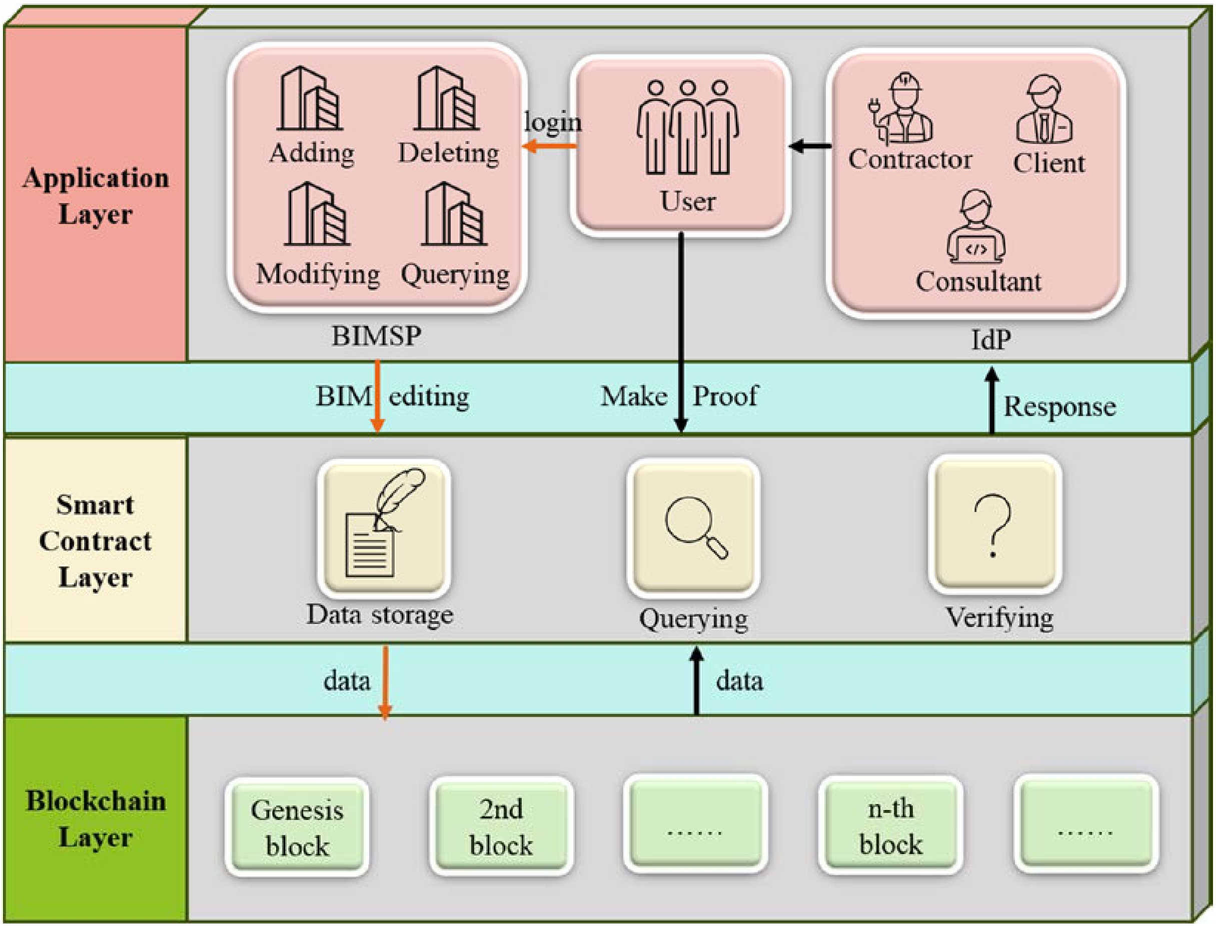


Fig. 2: Structure of the proposed zk-SNARKs-based identity authentication protocol

This paper focuses on the smart contract for proof verification, which implements an automatic authentication model based on the zk-SNARKs protocol. The zk-SNARKs protocol supports succinct proof verification by the one-way message communication between the prover and verifier. Its development processes involve five main steps:

1) Define the domain-specific data model to describe the BIM-related knowledge for identity authentication. For instance, to describe the editing history records of a door, the data of “editing_month”, “door_level”, and “editing_action” should be involved. The “editing_action” is further categorized into four subtypes: add, delete, modify, and query.

2) Describe the logic of the domain-specific data model to be proved using the NP statement such as Rank-1 Constraint Satisfaction (R1CS). An NP statement means that if you have a solution, it is computationally easy to prove it, but it is not computationally to find the solution. In this way, the ZKP protocol is completeness and soundness.

3) The proof circuit accepts some common parameters as input and generates a Common Reference String (CRS).

4) Generate proof about the proposition.

5) Verify the proof.

The core step is generating the NP statement of the domain-specific data model, namely the logic proof circuit. Many tools are developed to do this work, such as Zokrates, libsnark, snarkjs, etc. In this paper, the Zokrates toolbox, which is developed by Ethereum, is implemented to convert the BIM-related data model to the logic-proof circuit. A detailed example is presented in Part 3.

2.2 Workflow

The workflow of proving the identity to the blockchain system is depicted in Fig. 3. A user defined by IdP first requests a login to the blockchain system with a role confirmation process. Then, BIM stakeholders generate proof of the BIM-related knowledge, such as the editing of a BIM version at a specific time, to the blockchain. The smart contract for verifying the proofs is pre-deployed on the blockchain and verified automatically. If the proof is verified as true, a one-time password authenticates the user to log in. The login event will be recorded on the chain, too.

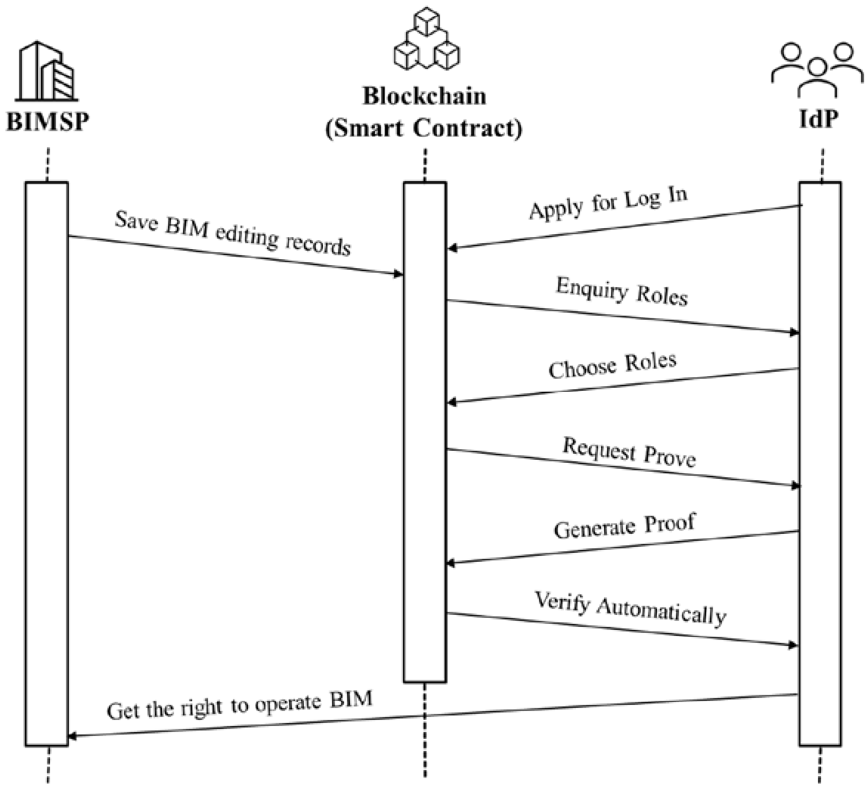
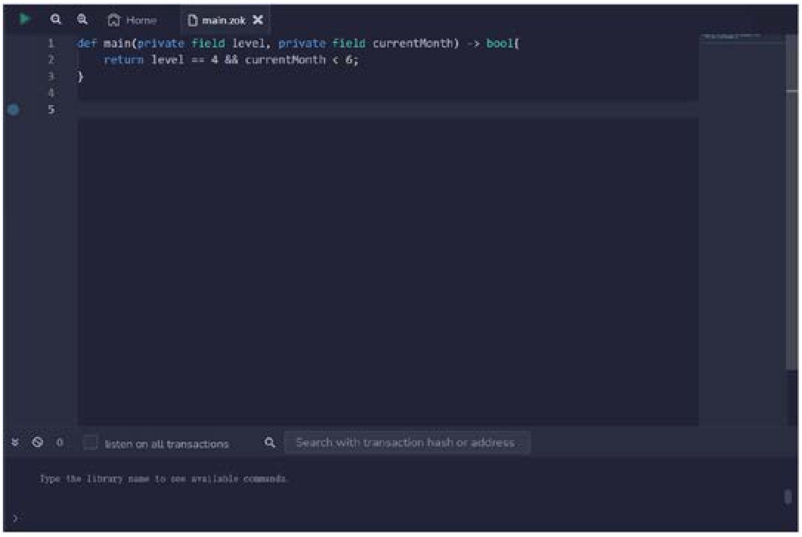


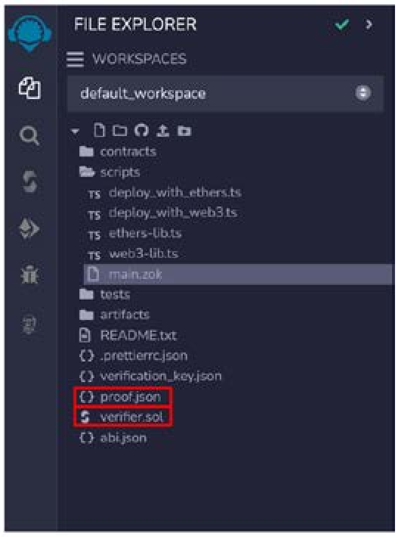
Fig. 3. The workflow of the proposed protocol

2.3 Software implementation

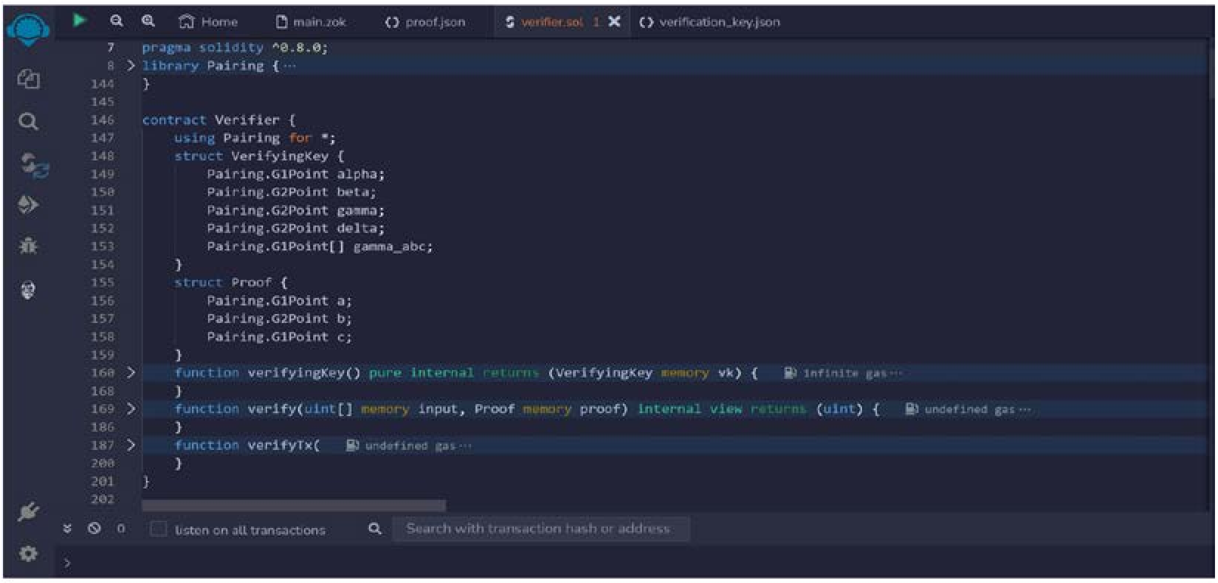
An identity authentication smart contract (IASC) is deployed on the test blockchain network by ZoKrates (Version 0.8, available at https://github.com/Zokrates/ZoKrates). ZoKrates (2023) is a toolbox for implementing zk-SNARKs on Ethereum, which provides functions such as trusted setup, libraries, and proving schemes et al. The Remix IDE is an open-source web-based IDE that creates, compile, tests and deploy Ethereum-based smart contracts on the blockchain network (Jain , 2022). Fig. 4 illustrates the interface of generating an IASC and deploying it on the test blockchain network by the Remix IDE.



(a) Definition of the logic circuit



(b) Generated proof and IASC



(C) An example of IASC

Fig. 4: Interfaces of Remix IDE. (a) define a logic circuit; (b) Generation of proof and identity authentication smart contract; (c) an example of IASC

As Fig. 4(a) shows, the circuit is declared in the ".zok" file alliance with the ZoKrates schema, the private filed type represents the secrete input that will not be revealed in the proof process and return a bool value that represents the verification result. A BIM user is able to generate a proof file, namely the "proof.json" file in Fig. 4(b), which will be sent to the blockchain for verification. The generated IASC is shown in Fig. 4(c), including five parts: (1) two data structures that describe the verification key and proof data; (2) three verification functions.

3. CASE PILOT

3.1 Case selection

A project at the University of Hong Kong (HKU) was selected in this section to demonstrate the proposed zk-SNARKs identity authentication protocol. The project was a modular construction project of a student residential apartment located at Wong Chuk Hong (WCH), involving 1,224 modules. Each module involves three main phases. Each module involves three main phases:

1) Manufacturing phase that the module is manufactured in the factory in Mainland China;

2) Logistics phase that transports the module from Mainland to Hong Kong through maritime transportation and land transport; and

3) On-site installation of modules.

3.2 Mapping of project workflow to zk-SNARKs

The fragmented construction phases and multi-disciplinary participants require high-level access control to the blockchain BIM collaboration platform. The IdP of this project defines three main stakeholders:

1) The main contractor. Paul Y. Engineering is the main contractor, and is responsible for module manufacturing and inspections, module transportation, and on-site installation. Paul Y. utilizes BIM for the on-site instructions and proposes potential changes to the consultant and client.

2) The lead consultant. Architecture Design and Research Group Ltd. (AD+RG) is the lead consultant for design and the key author and data contributor of BIM. Architecture, structure, water/drainage, and HVAC designers collaborate on the comprehensive BIM.

3) The client. HKU is the client of this project can access the whole BIM collaboration system.

According to the category of roles and responsibilities, the statements of the Zk-SNARKs-based authentication protocol of each group should be as follows:

1) Paul Y. Engineering: Browsing history of BIM. For example, "is the statement 'User A browse the architecture BIM Ver. 1.2 on 29th September' *True or False*?

2) AD+RG Ltd: Browsing and authoring history of BIM, including components' changes and revisions. For example, "Is the statement 'the *DELETE* operation of sliding windows/doors at level 4 was done before June' *True* or *False*?"

3) HKU: Browsing records of BIM models or related project information in the blockchain transactions. For example, "Is the statement 'so far, there have been 4 approved BIM changes in the structure domain' *True* or *False*?"

To map the project workflow to the proposed zk-SNARKs-based identity authentication protocol, a statement of BIM-related knowledge should first be converted to a computational problem. For instance, the statement "User A browse the architecture BIM Ver. 1.2 on 29Th September" should be converted as "if version == 1.2 and date == 29th Sep then result == True else result == False". Then, an NP statement such as R1CS should be developed. Specifically, R1CS is a sequence of three vector sets (*A, B, C*) that satisfy the equation $s \cdot A * s \cdot B = s \cdot C$, where s is the solution vector and $A,\ B,\ C$ are coefficient vectors. The simple "·" represents the inner product operation of vectors. The computational statement is converted into several simple expressions to represent the computation logic, such as $x \oplus y = z$ where "$\oplus$" represents the "$+$" or "$\times$" operations in the proof circuit. For the example computation statement, the operation is "$+$". In this way, the project workflow statement is converted to R1CS circuits for further computation.

3.3 Preliminary results

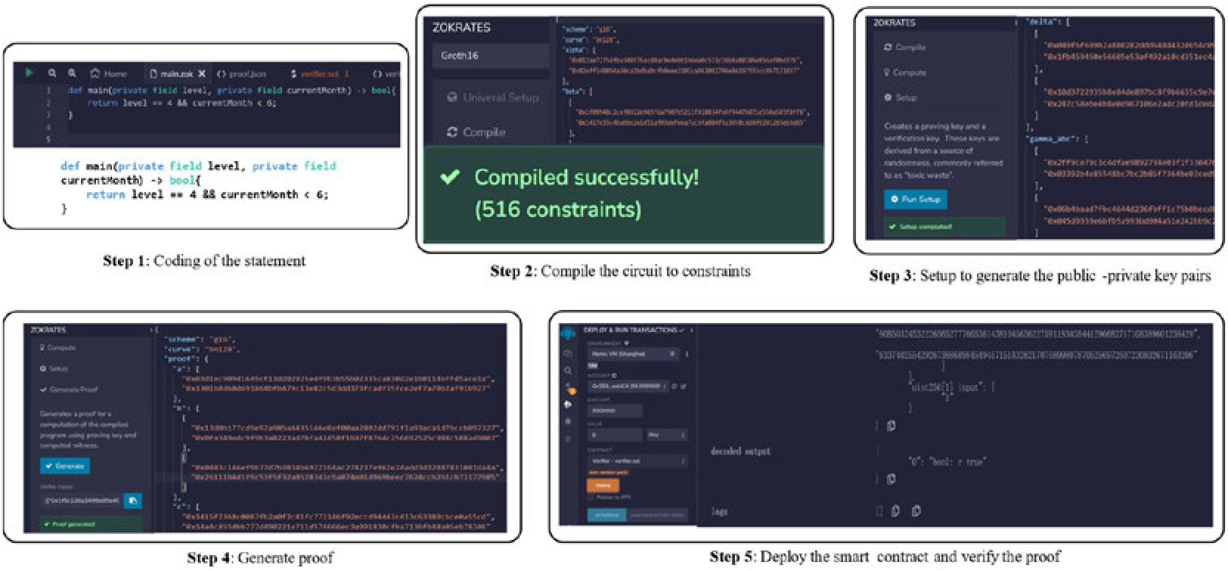


Fig. 5: An example of the identity authentication process of the project consultant.

Fig. 5 gives an example of the zk-SNARKs-backed identity authentication process of the project consultant. The Remix IDE (Ethereum 2023) is utilized to deploy the smart contract. The statement "the DELETE operation of sliding windows/doors at level 4 was done before June" is coded as a computation function firstly according to Sec. 3.2. Then, users can compile the function as a logic circuit with 561 constraints by the compile function provided by Remix IDE. The zk-SNARKs require setup to generate a public-private key pair for further proof generating, which is done in Step 3. After the setup process, BIM stakeholders generate proof through their private input, namely their secret knowledge. As Step 4 shows, the generated proof file is a JSON file that involves data of prove schema (elliptic curves) and a hash of proofs. After that, a smart contract with the suffix ".sol" is extracted and deployed on the test blockchain network in Step 5. Finally, the proof file is sent to the smart contract and verified. As **Errore. L'origine riferimento non è stata trovata.** shows, the verification of the consultant is true in Step 5.

4. DISCUSSION

The potential influences of the proposed Zk-SNARKs-based BIM user authentication protocol can be analyzed and discussed from different perspectives, including technology, business, and user.

From a technological standpoint, Zero-Knowledge Proof (ZKP) aligns effectively with on-chain knowledge. Through the synergy of Building Information Modeling (BIM) and blockchain, construction knowledge attains inherent transparency and becomes readily accessible via the distributed ledger. The blockchain records historical BIM operation activities, preserving collaboration traceability. Meanwhile, off-chain BIM files can be securely accessed via on-chain indexes. The amalgamation of on-chain and off-chain BIM-related data presents itself as suitable knowledge for user identity authentication. Consequently, the integration of ZKP and blockchain BIM emerges as a rational and achievable endeavor.

From a business standpoint, the identity authentication protocol based on Zk-SNARKs fosters a higher degree of reliability and trust in BIM-centered collaborations within the blockchain ecosystem. The adaptive access control, rooted in BIM knowledge, safeguards user identity privacy while accommodating an array of application scenarios, including bidding qualifications. Moreover, this identity authentication solution empowers traditional organizations and data providers to securely generate sensitive data.

From a user perspective, the utilization of ZKP empowers BIM stakeholders to efficiently create a suite of identity authentication smart contracts based on their project-specific knowledge. Nonetheless, the adoption of the zk-SNARKs-based identity authentication protocol demands a fundamental grasp of 'computation representation of knowledge.' In essence, users must formulate the logical representation of project-related knowledge. Regrettably, this prerequisite presents a barrier to the widespread adoption of ZKP.

5. CONCLUSION

The advent of blockchain introduces new prospects for transparent, immutable, and secure distributed BIM collaboration. Yet, owing to the inherently open nature of blockchain, the integrity of construction management faces significant threats from severe cybersecurity attacks, particularly password attacks. Establishing secure identity authentication mechanisms for data access within the realm of blockchain BIM becomes the cornerstone of trustworthy collaboration. However, conventional methods of identity authentication, such as the traditional public-private key pair or password, are susceptible to malicious exploitation. Enter zero-knowledge proofs (ZKP), a cryptographic technique empowering the prover to persuade the verifier without disclosing additional meaningful information about their claims. Consequently, ZKP is positioned to endorse password-free identity authentication, basing approvals on users' knowledge, thus effectively sidestepping the risk of malicious password theft.

This paper introduces a ZKP protocol, specifically zk-SNARKs, designed for identity authentication within the context of the blockchain BIM environment. Through the utilization of the zk-SNARKs protocol and on-chain historical BIM editing data, this study establishes an adaptive identity authentication process for collaborative efforts based on blockchain BIM. In contrast to conventional password or public-private key authentication methods, this study employs the knowledge of BIM and construction projects as the primary means of identity verification. ZKP ensures the privacy and security of this knowledge, effectively functioning as the safeguard to authenticate identities.

A pilot case implements the proposed protocol by deploying a smart contract on the test blockchain network. The results vividly illustrate the feasibility of the proposed method. Subsequently, we delve into the potential impact of ZKP from technological, business, and user perspectives. The theoretical contribution of this research hinges on the development of a zk-SNARKs-based identity authentication protocol. This protocol efficiently leverages a subset of on-chain BIM editing records. In practical terms, the workflow of the proposed identity authentication protocol guides BIM users through tasks such as creating domain-specific circuit descriptions of BIM knowledge, developing the smart contract, and deploying it on-chain using tools like ZoKrates and Remix IDE.

This research is subject to several limitations. Firstly, the zk-SNARKs protocol necessitates a trusted setup before generating proofs and theoretically could produce false proofs that appear valid to the verifier. Furthermore, the intricate domain-specific knowledge associated with blockchain-BIM-based construction management remains unexplored, warranting further investigation to formulate a specialized domain-specific language. Lastly, the case pilot's scope is confined to laboratory testing, necessitating more extensive trials in complex real-world project scenarios. As a recommendation for future studies, we propose the exploration of more advanced ZKP protocols, such as zk-STARK, to effectively address the aforementioned limitations.

ACKNOWLEDGEMENT

The work presented in this paper was supported by the Hong Kong Research Grants Council (RGC) (No. 17200221).

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LEVERAGING SMART CONTRACTS IN BUILDING INFORMATION MODELING (BIM) FOR UNIFIED PROJECT EXECUTION: A THEORITICAL FRAMEWORK.

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ABSTRACT: *Over time, several procurement methods have been adopted to facilitate the successful delivery of construction projects with minimal financial losses in order to offer maximum value to clients. In recent years, the Integrated Project Delivery (IPD) procurement model has been introduced for better overall financial performance. In this model, every member of the project team has a stake in overall profit or risk irrespective of the extent of their roles and change orders and correction of errors and omissions are managed effectively with minimal contractual disruptions. This paper aims to address some of the previously cited barriers in earlier scholarly work, and it proposes a conceptual framework that integrates two novel concepts towards tackling technological and financial barriers in adopting IPD namely, BIM and Smart Contracts (SC). A framework is developed for a BIM-blockchain-IPD whereby the BIM model is integrated with blockchain technology, thereby acting as an immutable and transparent information repository and a platform for interdisciplinary collaboration in Architecture, Engineering and Construction (AEC) projects. The smart contract feature of blockchain technology offers an automated equitable distribution of risk and reward amongst project stakeholders based on agreements at project inception. Thus, the research contributes to a more efficient project delivery method by avoiding information asymmetry amongst stakeholders through a tamper-proof, BIM-enabled Common Data Environment (CDE). The proposed framework is validated with qualitative analysis of information obtained based on AEC industry procurement workflows.*

KEYWORDS: *Integrated Project Delivery, Smart Contract, Blockchain, BIM, AEC, Common Data Environment.*

1. INTRODUCTION

The American Institute of Architecture defined Integrated Project Delivery (IPD) as “a project delivery approach that integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction” (AIA California Council, 2007).

Integrated Project Delivery can be broadly categorized as a type of relational project delivery arrangement (RPDA), developed to generate a cooperative and trustful climate for project implementation that requires an honest and open communication for establishment of a trustful relationship (Lahdenpera, 2012). One key element in this form of procurement process is an early integration of the project team at inception. The early integration of different project participants has a main influence on the optimization of the design and therefore also on the construction as processes become more consistent with less rework (Heidemann & Gehbauer, 2010).

This paper conceptualizes a scenario where blockchain technology, through smart contracts can be integrated with BIM to facilitate integrated project delivery, towards an improved procurement process. It begins with a terse review of relevant literature under a few thematic headings. Then, diagrammatic workflows are used to illustrate a theoretical framework and the interconnected networking of project stakeholders. After which, a use case scenario of a procurement workflow using smart-contract enabled BIM for IPD is used to describe the framework.

2. LITERATURE REVIEW

Project delivery methods continuously evolve to address the specific needs and concerns at the times and each method has implications on the cost, schedule and quality performance, albeit how much performance is typically affected is still unclear. (Sullivan, Asmar, Chalhoub, & Obeid, 2017). Various project delivery types have been used in the AEC industry globally such as Design Bid Build (DBB), Design-Build, Design Build Operate and 4) Construction Manager at Risk (Roy, Malsane, & Samanta, 2018). Lahdenpera (2012) highlighted six (6) key features of RPDA or a cooperative delivery approach namely; a cooperative culture, team formation, administrative consistency, commercial unity, planning emphasis and operational procedures (Lahdenpera, 2012). In collaborative projects, stakeholders must have a high level if shared understanding with respect to cooperation, control and coordination to achieve mutually desired outcomes. (Ali & Haapasalo, 2023). However, the complexity

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Oluwatoyin Lawal, Nawari Nawari, *Leveraging Smart Contracts in Building Information Modeling (BIM) for Unified Project Execution: A Theoretical Framework.*, pp. 352-359, DOI 10.36253/979-12-215-0289-3.34

of construction and the multiplicity of stakeholders and their interests raises the probability for disputes and conflicts. Alaloul et al (2019) described construction as a fertile seedbed for disputes. (Alaloul, Hasaniyah, & Tayeh, 2019). Kumar et al (2020) highlighted 14 factors which lead to dispute in construction in order of hierarchy, stating that ambiguous language of contract was the most influential factor, which may also lead to opportunistic behavior, delayed response to decisions and unrealistic expectations, which may in turn lead to poor communication between project partners, culminating together with other factors to cause payment delays and eventually project cost overrun (Kumar Viswanathan, Panwar, Kar, Lavingiya, & Jha, 2020).

2.1 Challenges and Limitations of Integrated Project Delivery

Construction supply chains have remained contested, fragmented and highly adversarial because of the conflicting nature of demand and supply (Cox & Ireland, 2002). Kahvandi et al (2019) highlighted for limitation categories for the use of IPD on projects namely; contractual, environmental, managerial, and technical ones and resolving contractual challenges is very effective in resolving environmental, managerial, and technical challenges. (Kahvandi, Saghatforoush, ZareRavasan, & Preece, 2019). In less developed construction sectors like Nigeria, practitioners are aware of IPD but not as proactive towards its application, of which technological, legal, financial and cultural issues are hindering its widespread adoption (Ebekozien, Aigbavboa, Aigbedion, Ogbaini, & Aginah, 2023). Similarly, lack of interest amongst stakeholders involved in the construction supply chain and negative perceptions about the efforts, risk and expenses required in implementing IPD are observed limitations to its use (Durdyev, Hosseini, Martek, Ismail, & Arashpour, 2020).

2.2 Smart Contract Solutions for Construction

Smart contracts (SC) are contract clauses written in computer programs that will automatically self-execute when predefined conditions are met. They consist of transactions essentially stored, replicated and updated in distributed blockchains (Zheng, et al., 2020). The construction industry worldwide is known for its adversarial working relationships which exist between the stakeholders (Phua & Rowlinson, 2003). Young-Ybarra & Weirsema (1999) found trust to be the only component of social exchange theory that had a positive effect on flexibility of strategies (Young-Ybarra & Wiersema, 1999) Pishdad-Bozorgi (2017) explored trust dynamics on real world IPD projects and both case studies used in the research confirmed that IPD was more effective in building trust than traditional delivery method (Pishdad-Bozorgi, 2017).

2.3 Blockchain and BIM in Construction

The AECO industry began to actively deploy BIM on projects in the early and mid-2000s (Jung & Lee, 2016). In a scientometric review, Liu et al (2019) mentioned that research in the field of BIM has been developing continuously and has completely subverted the traditional operation mode of AEC industry, while attracting more researchers' attention at the same time (Liu, Lu, & Peh, 2019). Lawal & Nawari (2022) proposed a BIM-blockchain unified ledger to provide traceability for building components for a more auditable real estate valuation. (Lawal & Nawari, 2022). One of the most commonly researched blockchain applications in AEC is its integration with BIM for improved workflows and processes amongst construction stakeholders, thereby fostering improved collaboration. (Nawari & Ravindran, 2019) (Zhang, Doan, & Kang, 2023). BIM adds one or more additional dimensions to traditional design approaches which is the information layer that describes physical properties of building components. Innovations to the blockchain-BIM integration has made it possible for a shared platform like BIM to provide security of sensitive data either through a confidentiality minded framework (Tao, et al., 2022) or by using lightweight blockchain-as-a-service prototypes in the case of emergency construction projects (Tao, et al., 2023). Applications of blockchain-BIM are prevalent in pre-construction stage for secure and traceable control of design documentation, however, as the maturity level of both technologies increase, this integration will cut across project lifecycles.

3. THEORETICAL FRAMEWORK

The use of Building Information Models (BIM) for generation of information has become widespread in the Architectural, Engineering and Construction (AEC) industry in the past decade. BIM also refers to the virtual process and workflow that encapsulates all aspects, disciplines and systems of a facility or asset within a unified virtual model to facilitate a more accurate and efficient real-time collaboration (Azhar, Khalfan, & Maqsood, 2012). BIM is a revolutionary technological development that is rapidly reshaping the AEC industry and transforming the way we build, and the AEC industry have pushed stakeholders to use BIM extensively in a streamlined and integrated manner over the building lifecycle (Liu, Lu, & Peh, 2019). BIM helps to discover collisions which usually occur during construction in a high number and therefore, the team is able to resolve those already during the design phase. A huge amount of time, rework and redesign can be eliminated (Heidemann & Gehbauer, 2010).

The image in figure 1 shows an interconnected loop between all project stakeholders and between stakeholders and the BIM model, which is housed in a cloud-based Common Data Environment. Earlier studies have proposed a Common Data Environment (CDE) for secure data storage of digital assets, interdisciplinary coordination, management, and versioning of information containers (Sreckovic, et al., 2021) (Wang, Wu, Wang, & Shou, 2017) (Pishdad-Bozorgi, Yoon, & Dass, 2020). Figure 1 below is a diagram of interrelationship between all project stakeholders. A cloud-hosted blockchain CDE which is the agreed information repository that records all additions and alterations to the contained information, is used to house a shared BIM model. Blockchain provides a decentralized, automated and secured financial platform which enables multiple parties to control and track financial transactions (Elghaish, Abrishami, & Hosseini, Integrated project delivery with blockchain: An automated financial system, 2020).

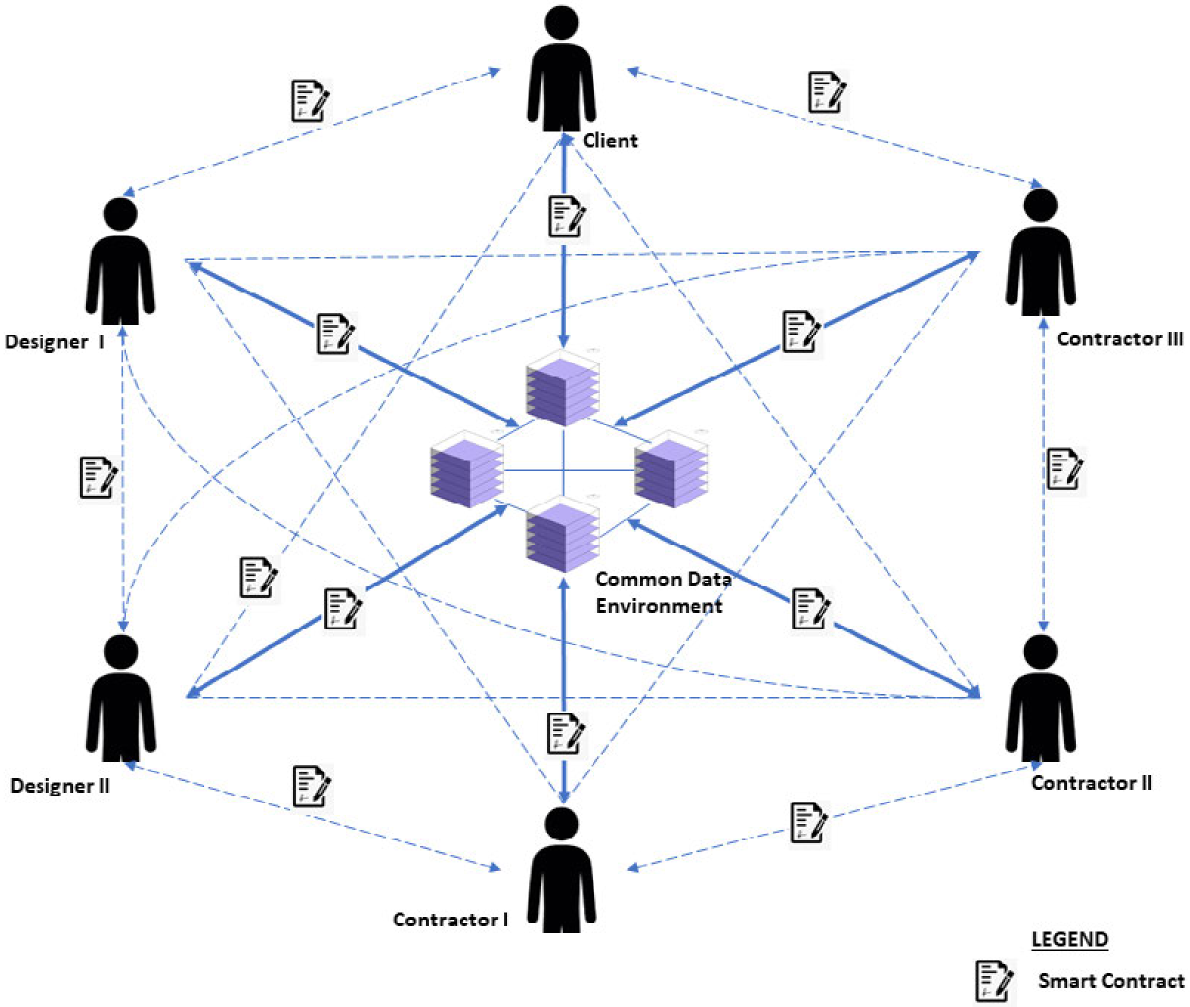

Figure 1: Network of project team and BIM model, with smart contracts managing the interrelationships

The CDE connects to a front-end interface wherein all participants are visibly interconnected and smarts contracts embedded between every interconnection act as triggers to automate and record the transition to a new phase of engagement once certain conditions / project milestones are reached, as confirmed by the BIM and a physical model twin contained in the CDE. The physical twin is derived through the use of IoT and BIM. The emergence of IoT has transformed the way data is shared across various sources (Barricelli, Casiraghi, & Fogli, 2019). Digital Twins refer to the process of merging the virtual world and real world, and has become a widely accepted tool in the Architecture, Engineering, and Construction (AEC) industry due to its ability to enhance cross-disciplinary collaboration (Sahal, Alsamhi, Brown, O'Shea, & Alouffi, 2022). The linear flow of information and smart contract deployment referred to in Figure 1 is shown below in Figure 2.

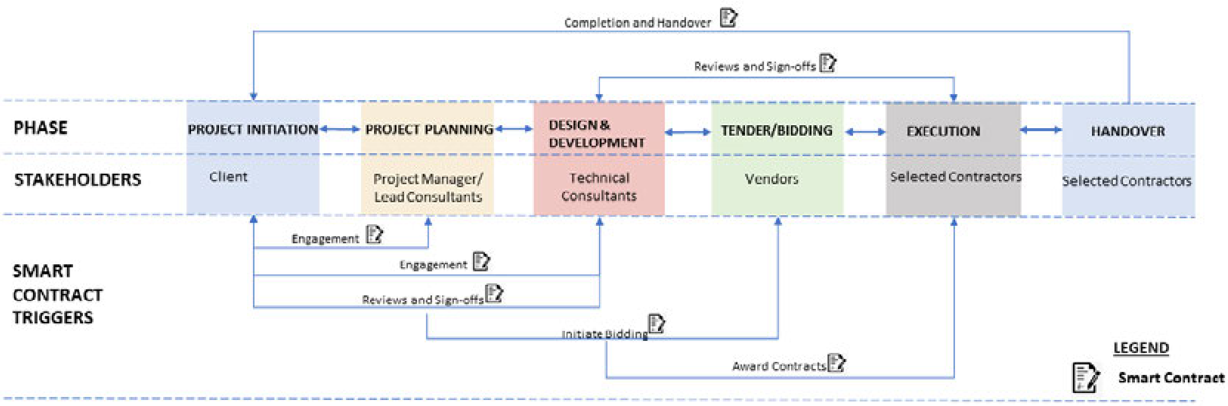

Figure 2: Linear Information Flow in Integrated Project Delivery

Smart contracts are deployed at instances where a client 1) engages a new service provider, 2) reviews and signs off on information, 3) initiates a bidding process, 4) appoints a contractor and also when consultants 1) review and sign-off on documents and procedures submitted by contractors and 2) signs off on construction at project completion.

4. USE CASES

The use case scenario will be discussed under to main headings; 1) BIM-enabled Integrated Project Delivery and 2) Smart Contract Payment Method through BIM Monitoring.

4.1 BIM-Enabled Integrated Project Delivery

The ability of BIM to replicate physical scenarios throughout the building lifecycle makes it suitable for collaborative workflows. BIM and IPD are process innovations that are driven by technology and reconfigure social relationships (Rowlinson, 2017). Existing literature suggests that BIM and/or IPD can dramatically enhance project performance from conceptualization through building management, and ongoing operations. (Ilozor & Kelly, 2012). This scenario leverages the abundance of research in BIM and IPD. The Project Manager (PM) or Lead Consultant (LC) creates the initial BIM model and shares it with the client, other consultants and all the contractors as they join the project. The PM/LC acts as the network administrator throughout the project. All changes as well as milestones are securely recorded in the back-end interface using the smart contracts and these milestones are visible to all members of the project team, so every party knows what stage every aspect of work is. Contract administration is enumerated under section 4.2 using the principle of Common Pool Resource (CPR). BIM-based solutions for IPD have also been proposed to enable accurate cost estimation at project inception when little information is available on the front end (Elghaish, Abrishami, Hosseini, & Abu-Samra, 2021)

4.2 Smart Contract Payment Method Through BIM Monitoring

Common-pool resources are systems that generate finite quantities of resource units so that one person's use subtracts from the quantity of resource units available to others (Ostrom, Gardner, & Walker, 1994). Hunhevics et al (2020) suggested that the governance of a Common Pool Resource (CPR) scenario was a useful guide to future research and applications of blockchain in construction. (Hunhevicz, Brasey, Bonanomi, & Hall, 2020). This phase of the use case deploys the combination of the BIM model, the model's physical twin on site using IoT technology to implement Digital Twins as discussed earlier, and the CPR as illustrated in Figure 3 below. The diagram below is a blow-up of the CDE shown in Figure 1.

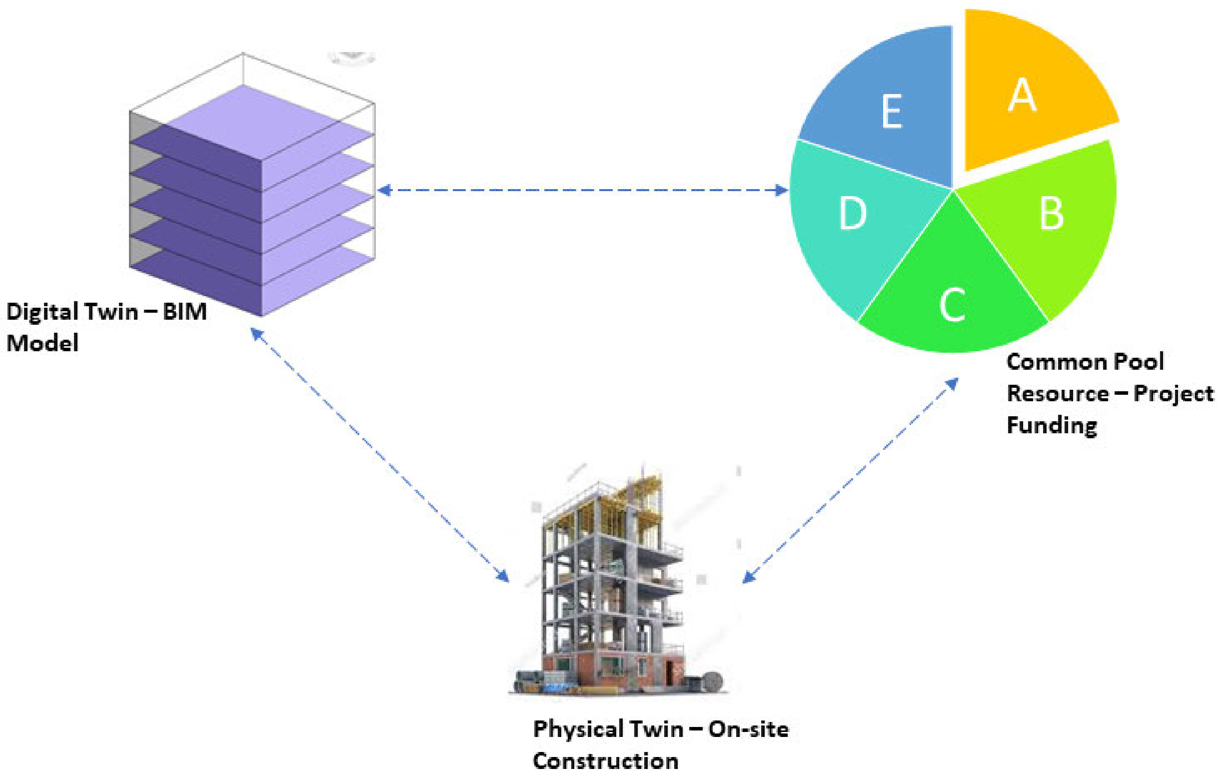

Figure 3: Components of the Common Data Environment

Earlier sections have shown how workflows of several project stakeholders can be integrated. However, contract administration, clarity of contract language and timely payment disbursement are some of the factors which make traditional procurement methods cumbersome. In this instance, the human component of contract administration and payment disbursement are eliminated by depositing project funds in an escrow account, otherwise referred to as the CPR. The CPR acts as a third-party agent except that it is not triggered by any one individual. Once a contract milestone is reached by any of the project stakeholders, the digital twin pair of the BIM model and the IoT powered construction communicate with the CPR to trigger a smart contract between the client and the corresponding project stakeholder. Payment is automated to such stakeholder based solely on the attainment of an earlier agreed milestone.

5. CONCLUSION

This research has built upon a preponderance of academic endeavors in the field of BIM, Integrated Project Delivery, Blockchain, and Smart Contracts within the AEC industry. With recent academic interests in the use of BIM at the forefront of some of the most cutting-edge innovations in construction and deployment of smart contracts to facilitate payment in construction projects. Beginning with a terse literature review which discussed general scholarly efforts around Smart Contracts and IPD, the literature review was broken down into thematic areas like challenges and limitations of IPD, Smart Contract (SC) solutions for construction and blockchain-BIM integration in construction. A theoretical framework was proposed which situates all stakeholders in an interconnected loop and in connection with the blockchain-enabled BIM simultaneously. The BIM is shared through a Common Data Environment (CDE). The linear flow of information/instruction in this form of IPD is also illustrated. Two use case scenarios helped to visualize the applicability of this framework. The first uses a BIM-emabled IPD where the shared BIM model facilitates the construction-phase collaboration amongst the project team whereby the Project Manager or Lead Consultant acts as a network administrator and changes are recorded using Smart Contracts. The second use case deploys SC payment method through BIM monitoring. In this case, a Common Pool Resource (CPR) warehouses the funds required for the project and BIM monitoring such as IoT-enabled Digital Twin can be synchronized with CPR and SC to trigger payment instructions once physical progress corresponds with the pre-coded digital milestone on the BIM model. Although this concept offers a solution to streamline construction workflows, further research is required to elucidate on the algorithmic workings of smart contract deployment in a BIM-enabled IPD.

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ISAFEINCENTIVE: TRANSFORMING CONSTRUCTION SAFETY CULTURE THROUGH BLOCKCHAIN INCENTIVES

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ABSTRACT: *A significant challenge has long persisted in the construction industry: the lack of a robust incentive system to encourage and motivate workers to prioritize safety. While safety culture has been recognized as crucial, traditional approaches to incentivizing safe behaviours often encounter roadblocks, such as heavy documentation processes, recognition delays, and resource allocation difficulties. This paper addresses this problem by introducing an innovative approach to incentivize and cultivate a safety culture in the construction industry. iSafeincentive integrates blockchain technology and computer vision to develop a novel solution revolutionizing safety monitoring and incentive distribution. Computer vision technology is employed for real-time analysis of safety conditions based on on-site images, ensuring the immediate identification of safe practices. Simultaneously, blockchain technology safeguards the incentive distribution process's integrity and transparency, addressing traditional methods' shortcomings. The findings suggest that iSafeincentive offers an efficient and secure method for rewarding safe activities among workers. Furthermore, the integrated platform offers a promising pathway to enhance job site safety practices, ultimately reducing accidents and incidents within the construction sector.*

KEYWORDS*:* *Safety Culture, Incentive Programs, Blockchain Technology, Computer Vision, Construction Industry, Workplace Safety*

1. INTRODUCTION

The construction industry presents a dynamic workplace where the constant spectre of accidents and injuries casts a shadow over operations (Lim et al., 2021; Won and Soo, 2021). A robust safety culture within this sector is imperative, where safety transcends mere compliance and becomes an integral core value deeply entrenched in the organizational ethos. Such a culture is characterized by a collective commitment to hazard identification, risk mitigation, and the seamless integration of safety into all facets of work ((Zou, 2011); (Barg *et al.*, 2014); (Aksorn and Hadikusumo, 2008)). However, several critical challenges impede the development of this vital safety culture. First and foremost, construction sites often lack effective data management systems and reliable inspection and monitoring mechanisms. This deficit hinders the timely identification and rectification of potential hazards(Alexander Laufer and G. Jenkins, 1982). Secondly, there exists a dearth of incentive programs designed to motivate construction workers to prioritize safety ((Biggs, Sheahan and Dingsdag, 2005)). These programs have the potential to significantly reduce accidents and incidents on construction sites, fostering a resilient safety culture.

It is essential to emphasize the role of management in motivating construction workers to prioritize safety. Management must actively incentivize safe practices, linking desired outcomes to performance ((Alexander Laufer and G. Jenkins, 1982)). Furthermore, cultivating the right safety knowledge interpersonal skills, and fostering appropriate attitudes and beliefs are pivotal in nurturing a positive safety culture within the workforce ((Biggs, Sheahan and Dingsdag, 2005)). (Mohammadi, Tavakolan and Khosravi, 2018) provides insights into the multifaceted factors influencing safety performance in construction projects. (Helander, 1991) underscores the importance of monetary incentives as a catalyst for investing in construction safety. These findings collectively emphasize the significance of providing incentives, improving management practices, and shaping workers' beliefs and attitudes toward safety.

Incentives within the construction industry have shown a demonstrably positive impact on safety practices among workers ((Zulkefli, Ulang and Baharum, 2014)). They serve as structured mechanisms for recognizing and reinforcing safe practices, thereby contributing to amplifying and consolidating safety standards within the construction workforce. (Tang *et al.*, 2008) emphasizes the need for incentives in the Chinese construction industry, advocating for alignment with project features to enhance project delivery efficiency. (Huang and Sun, 2009) delves into various incentive smart contracts and their design principles, while Tinus (2014) highlights concerns regarding their impact on work productivity. (Nurul Fieqah and Ahmad Kazimi, no date) shed light on the challenges of implementing Occupational Safety and Health Act (OSHA) requirements, which can exacerbate administrative burdens and delay incentive distribution. It is crucial to address these issues and develop more efficient and streamlined incentive methodologies in construction. These methodologies should alleviate documentation burdens and enhance project performance, ensuring a harmonious balance between safety and economic sustainability.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Mehrtash Soltani, Dohyeong Kim, Akeem Pedro, Jaehun Yang, Si Tran, Doyeop Lee, Chansik Park, *iSafeIncentive: Transforming Construction Safety Culture through Blockchain Incentives,* pp. 360-367, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.35

In summary, while incentive programs in construction can significantly enhance safety performance, their long-term effectiveness requires continuous evaluation and strategic resource allocation. Addressing challenges associated with traditional incentive methods is essential to boost safety and productivity in the industry. Streamlining the monitoring process is critical, as current safety inspections suffer from issues like infrequent and inadequate assessments, exacerbated by limited resources and human errors. Moreover, a shortage of safety professionals leads to less thorough evaluations. A significant limitation is the absence of a comprehensive incentive system aligning with inspections and rewarding safe behavior.

To effectively address these challenges, this study aims to develop and implement an innovative incentive system that harnesses blockchain technology and computer vision. This system is designed to enable real-time monitoring and recognition of safe behaviors exhibited by construction workers to comprehensively enhance safety practices across various construction sites.

2. LITERATURE REVIEW

In recent years, blockchain technology has gained substantial traction within the construction industry, presenting novel solutions to address enduring challenges. These studies investigate blockchain technology's adoption and potential applications, specifically focusing on its capacity to enhance efficiency, transparency, and safety in construction operations. For example, several studies have adopted blockchain for enhancing information management in Modular Integrated Construction. (Pan Zhang, 2023) employs game theory to delve into this subject, highlighting the pivotal role of diffusion rates influenced by benefits, costs, and government subsidies. The study advocates for implementing pilot projects and governmental incentives to facilitate adoption. In another study, (Minju Kim, 2023) introduces a blockchain-based system to optimize off-site construction supply chains. Using Bayesian updating and incentives, the study aligns contractor and supplier decisions, ultimately improving transparency and reliability.

Another investigation by (Pan Zhang H. W., 2023) employs game theory to analyze the adoption decisions surrounding blockchain technology in Modular Integrated Construction. This study echoes the importance of pilot projects and government incentives as drivers of adoption. (Hossein Naderi, 2023) introduces a decentralized application utilizing blockchain and computer vision to incentivize construction safety through token rewards. The application autonomously evaluates safety performance and issues unique Non-Fungible Tokens (NFTs) as rewards while maintaining user confidentiality. It presents promising prospects for various domains; however, scalability issues and challenges related to individual incentivization must be addressed through further development to expand its practical applications. In addition, (Namya Sharma, 2022) provides an exhaustive review of 33 global strategies for managing Construction and Demolition waste, focusing on integrating Circular Economy principles and lifecycle thinking, particularly in the Indian construction sector.

In another application, (Wenli Yang, 2022) proposes a master-slave chain model and a hybrid consensus algorithm to enhance the efficiency and security of multidomain conversational interactions on a blockchain. It effectively manages various scenarios concurrently while maintaining fault tolerance. However, it faces challenges related to high capacity demands due to diverse data types, necessitating further exploration of big data verification and consistent storage management. Finally, (Liupengfei Wu, 2022) introduces a blockchain-based supervision (BBS) model to improve supervision and security in cross-border logistics within modular construction. The model employs incentives to encourage data sharing, resulting in enhanced product accountability and data traceability compared to centralized platforms. Nevertheless, it encounters limitations, such as the potential for opportunistic behavior in data entry and a static incentive mechanism.

In conclusion, while these studies contribute significantly to our understanding of blockchain adoption and its applications in construction and related domains, they collectively share limitations such as theoretical orientation, lack of empirical evidence, oversimplified stakeholder models, and the need for further practical validation. Addressing these limitations is crucial for advancing the field and ensuring the real-world viability of these concepts.

3. RESEARCH METHOD

3.1 Process

To address the objective of this study, the approach is to integrate computer vision technology, which allows for the automated analysis of safety conditions from site images. Computer vision eliminates the need for extensive manual inspections and enables more accurate and efficient safety assessments. With reduced human intervention, safety assessments become consistent and unbiased, greatly enhancing the reliability of inspection results.

The integration of blockchain technology, in conjunction with computer vision (Figure 1), presents a groundbreaking shift in the construction industry's management of safety inspection data. Blockchain's immutability is pivotal in upholding the integrity and permanence of safety inspection records. Once safety data is securely recorded on the blockchain, it becomes impervious to alteration or tampering, instilling a high level of confidence in the precision and authenticity of the information. This characteristic is paramount in safety inspections, as it safeguards historical safety assessment records, reinforcing their credibility for compliance verification, auditing, and accountability purposes. Furthermore, the symbiotic fusion of blockchain and computer vision technologies fosters enhanced collaboration among various stakeholders involved in construction projects. Digital platforms, underpinned by these innovative technologies, enable real-time data sharing and communication. This digital transformation empowers project managers, safety officers, construction workers, and regulatory authorities to access and comprehensively review crucial safety inspection data promptly.

Consequently, stakeholders can respond swiftly to emerging safety concerns, coordinate preemptive measures, and effectively address potential hazards, ultimately cultivating a safer work environment. This technological convergence signifies a pivotal departure from traditional paper-based data collection methods, significantly enhancing the efficiency of safety inspection processes. Eliminating manual data entry and paperwork markedly reduces the likelihood of errors and omissions, elevating the precision of safety assessments. Furthermore, digital platforms support automated data analysis, providing real-time insights and reports. This data-driven approach empowers safety officers and managers to make well-informed decisions expeditiously, proactively mitigating risks and amplifying overall safety performance.

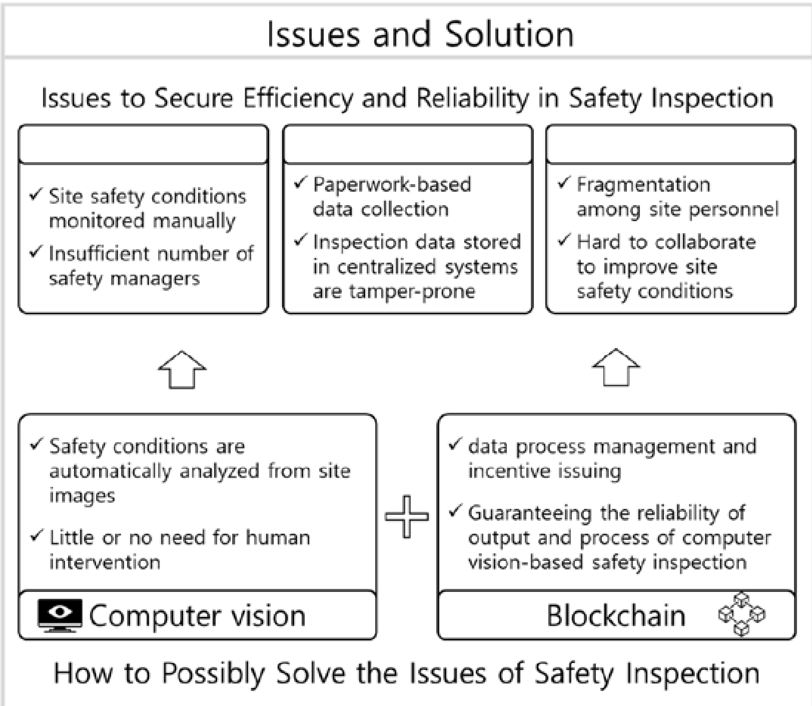

Fig. 1: The existing condition of safety inspections and suggested technological solutions to mitigate their challenges.

In the contemporary construction industry, a conspicuous challenge resides in inadequate motivation and incentives to stimulate safety performance and regulatory compliance among its workforce. This deficiency results in a series of interconnected issues that reverberate throughout the construction ecosystem. Site managers, at times overwhelmed by their responsibilities and bereft of tangible incentives for meticulous oversight, may inadvertently neglect safety protocols or make critical errors. Furthermore, the scarcity of qualified site managers compounds these challenges, leading to lapses in enforcing safety measures. Concurrently, the reliability of management records concerning safety compliance becomes questionable, diminishing the effectiveness of oversight mechanisms. This confluence of factors not only jeopardizes the well-being of construction personnel but also raises concerns about the quality and safety of the final built environment.

In response to these pressing concerns, as depicted in Figure 2, a multifaceted approach is emerging within the construction industry, driven by the amalgamation of technological innovation and incentive systems. This approach extends from project bidding, wherein contractors can accrue additional points or insurance rate discounts for committing to stringent safety and quality standards, to insurance and guarantee providers offering reduced premiums as rewards for safety adherence. Notably, the proposal of a token-based incentive system underpins this transformation, leveraging blockchain and verification technologies to bolster the adequacy and reliability of information generated within the construction milieu. This incentive-driven paradigm fosters voluntary safety activities among all stakeholders, from equipment and material suppliers to structural consultants and safety inspection agencies. By incorporating bottom-up perspectives, this holistic shift aspires to invigorate safety culture within construction, ensuring that every participant is vested in the collective goal of elevating safety standards and mitigating risks across the industry.

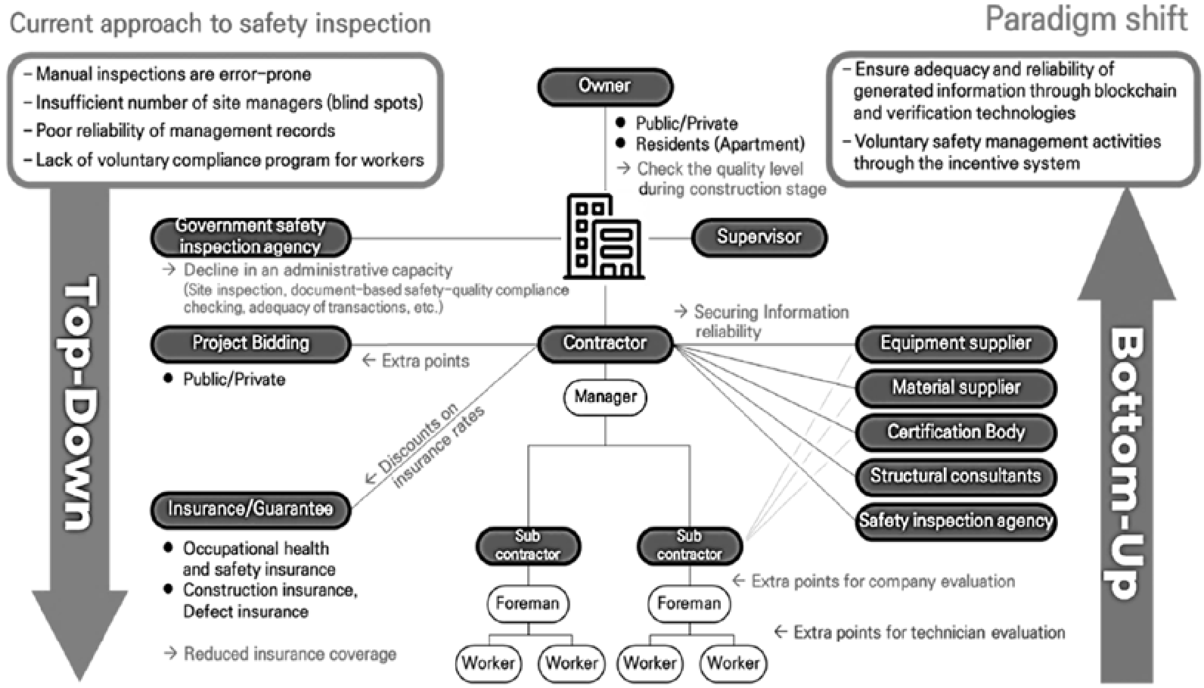

Fig. 2: Token-based incentive system

Furthermore, utilizing blockchain-based evaluations introduces a novel incentive structure that encourages the voluntary participation of managers and workers in safety activities. Rewards are distributed following the evaluation results, directly linking safety performance and tangible incentives. This incentivization model can significantly enhance safety awareness and engagement among construction personnel. In addition to rewards, the system can incorporate mechanisms such as additional bidding points, safety ratings, and reductions in insurance fees, all contingent upon the evaluation scores of the workforce held by companies. This multifaceted approach promotes safety at individual and organizational levels. It aligns safety objectives with broader project and financial considerations, making it a comprehensive and effective strategy for improving safety conditions in the construction industry.

3.2 Applications

3.2.1 Data management

The process of safety condition analysis from on-site images is a multifaceted procedure that seamlessly integrates automated image analysis through computer vision and robust data management, all while leveraging the security of blockchain technology. This comprehensive process involves regular and irregular inspections facilitated by deep learning-based models and cloud-based computing resources. In the first step, regular safety inspections are conducted as scheduled assessments of construction sites. Various devices, such as smartphones or cameras, capture images during these inspections. Subsequently, the captured images are uploaded to a cloud-based system for further analysis, combining the power of computer vision for real-time safety assessment. As shown in Figure

3, once images are uploaded, the inspection process is initiated through user queries and system management. Users interact with the system to initiate inspections based on predetermined intervals or specific triggers, ensuring that safety conditions are consistently monitored using computer vision technology. The system, in turn, effectively manages the entire inspection process, overseeing data collection, analysis, and database management, all while benefiting from the transparency and security of blockchain integration. This systematic approach ensures that inspections are conducted regularly and streamlines the overall process, reducing delays and improving safety outcomes. A key aspect of this procedure lies in data management, further enhanced by blockchain technology. Within the cloud-based system, various types of data are meticulously handled. This includes system management data to maintain the integrity and functionality of the inspection system, project data to manage project-specific details, and user data to regulate access rights and profiles. Inspection data remains at the core of this process, involving records of all inspections and associated metadata such as timestamps, geospatial information, media types, and automatic extraction of relevant metadata from the images. Blockchain technology ensures the immutability and transparency of these critical data records, providing a secure and tamper-proof foundation for the entire safety analysis and incentive distribution process.

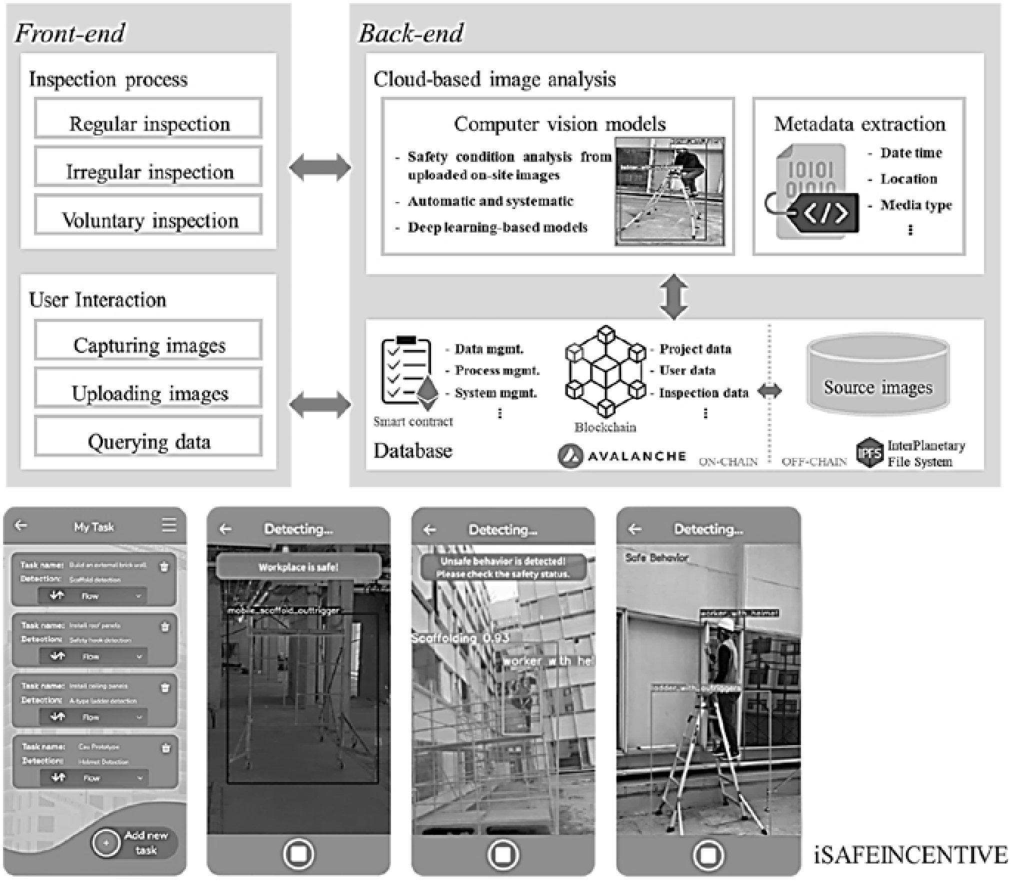

Fig. 3: Blockchain & Computer Vision Integration

3.2.2 Incentive mechanism

The token distribution process within the iSafeincentive platform, facilitated by blockchain technology, is characterized by a systematic sequence of actions. Commencing with continuous monitoring by the platform's AI detectors, the focus is assessing job site activities, including adherence to Personal Protective Equipment (PPE) regulations and safe conduct. Subsequently, vetted data undergoes scrutiny and validation to ensure accuracy and reliability. At the core of this process are smart contracts, meticulously crafted with predefined criteria and rules. These smart contracts serve as the automation engine, enabling the precise allocation of tokens in response to identified safe activities. Tokens are directed to the workers' digital wallets, tightly linked to their unique blockchain identities. Simultaneously, each transaction is recorded within the blockchain ledger, a fundamental feature that underpins transparency and traceability.

Worker notification follows promptly, serving dual purposes: acknowledging the safe behaviors observed and motivating continued adherence to safety protocols. Furthermore, this approach establishes an efficient and transparent record-keeping system. Figure 4 represents the utilization of blockchain technology to streamline the token distribution process. This systematic and secure procedure inspires trust among all stakeholders, enabling workers to employ their tokens in various capacities while cultivating a resilient safety culture within the construction industry.

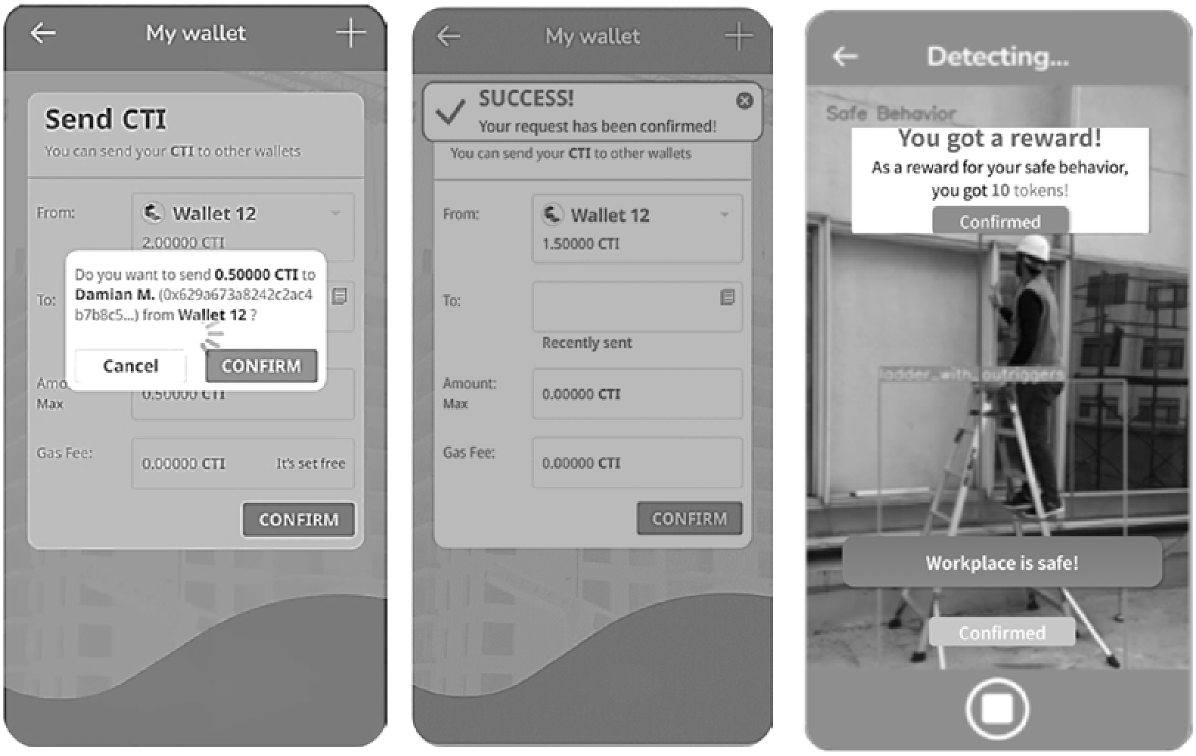

Fig. 4: The procedure for transmitting tokens once the safety measures have been verified through blockchain technology.

4. CONCLUSION

In conclusion, safety culture is vital in the construction industry, significantly influencing safety performance and outcomes. Empirical evidence supports the importance of a safety culture in reducing accidents and incidents within construction organizations. Motivating construction workers to prioritize safety through incentive programs has been crucial. Incentives encouraged safe behaviors, recognized individual efforts, and fostered a collective sense of responsibility for safety. However, as discussed earlier, current incentive methodologies face challenges, including burdensome documentation requirements, delays in distribution, and resource allocation issues. Streamlining documentation processes, reducing distribution delays, and optimizing resource allocation have been essential steps to enhance the effectiveness of incentive programs.

In this study, iSafeincentive has been developed by integrating computer vision and blockchain to automate safety assessments, improving accuracy and efficiency and ensuring the integrity and immutability of safety records and incentives. Blockchain-based incentives have linked safety performance to tangible rewards, enhancing safety awareness and engagement among construction personnel. This multifaceted approach has aligned safety objectives with broader project and financial considerations, demonstrating its potential as a comprehensive strategy for improving safety conditions in the construction industry.

The safety condition analysis process from on-site images combined automated image analysis with systematic inspection strategies, ensuring regular and reliable safety assessments. Token distribution through blockchain technology followed a systematic sequence, promoting safe behaviors and cultivating a resilient safety culture within the construction industry. Overall, these innovations held great potential for enhancing safety and productivity in construction.

ACKNOWLEDGMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (No. NRF-2022R1A2B5B02002553) and Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (No. NRF-2020R1I1A1A01073167).

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MULTI-ASPECTUAL KNOWLEDGE ELICITATION FOR PROCUREMENT OPTIMIZATION IN A WAREHOUSE COMPANY

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ABSTRACT: *Efficient optimization of business processes required a profound understanding of expertise provided by domain specialists. However, extracting such insights can indeed be a laborious and time-consuming endeavour. This paper introduces the Multi-Aspectual Knowledge Elicitation framework (MAKE4ML) — a novel approach designed to effortlessly and effectively extract valuable information from domain experts. This framework inherently facilitates the development of machine-learning models capable of optimizing business processes, thereby diminishing reliance on experts. The framework's application within a food warehouse company is showcased, specifically targeting the enhancement of the procurement process. The employed methodology revolves around conducting comprehensive interviews with procurement experts, thereby enabling a meticulous exploration of diverse facets inherent to a business process. Subsequently, the gathered insights are employed to conceive and calibrate a machine learning model (time series forecasting). This model effectively emulates the domain experts' proficiency, offering invaluable decision-oriented insights. The outcomes of this study show that our framework allows efficient knowledge elicitation, which is a pivotal factor in formulating and deploying a bespoke machine-learning model. The proposed approach can be extended into various other business processes, thereby paving the way for operational refinement, cost reduction, and amplified efficiency.*

Keywords*: domain experts, knowledge elicitation, multi-aspects, machine learning, procurement optimization, warehouse, technology acceptance.*

1. INTRODUCTION

The growing demand for digitalization and process optimization has led to the integration of machine learning (ML) models across industries. This integration often requires insights from domain experts, necessitating the extraction of pertinent information to design tailored ML models. Researchers and ML engineers have employed various techniques, such as feature selection and knowledge elicitation, to enhance model accuracy while ensuring successful technology adoption. Studies have highlighted the challenges of knowledge elicitation, which significantly affect ML performance across disciplines. Researchers are increasingly exploring human involvement in ML workflows (D'Angelo & Palmieri, 2020; Park et al., 2023; Sundin et al., 2022; Wang et al., 2021), combining expert knowledge with data from diverse sources (Ademujimi & Prabhu, 2021; Ben Brahim et al., 2022; Hu et al., 2019; Huang et al., 2019; Lee et al., 2020; Seymoens et al., 2019), and innovative ways to extract insights (Afrabandpey et al., 2019; Campos et al., 2018; Cheung et al., 2011; Crerie et al., 2009; El-Assady et al., 2020; El-Assady et al., 2019; Mantik et al., 2022; Možina et al., 2018; Park et al., 2021; Yazici et al., 2022; Young et al., 2022).

First, human involvement in ML workflows referred to as "Human-in-the-loop", aims to create cost-effective prediction models by incorporating human knowledge during data preparation and refinement stages. Secondly, the integration of expert-derived knowledge with data from sources like sensors refines training objectives and contextual alignment, as standard sensor data might lack external factors' consideration. Finally, Intuitive techniques (e.g., decision-mining, process mining) bridge gaps between ML engineers and multi-disciplinary experts, translating meaningful insights into ML model specifications.

The central research question is: "How can we extract meaningful knowledge from domain experts for designing ML models while ensuring user acceptance?" To address this, a comprehensive framework is proposed, involving multi-aspectual knowledge extraction, translation into ML specifications, visualizing business workflows, and capturing decision-making rules and constraints. Key contributions include a multi-disciplinary knowledge extraction framework, translating knowledge into ML and software specifications, and visualizing business workflows and decision rules. The framework's efficacy is demonstrated in a warehouse setting, focusing on procurement. Experimental results reveal the successful extraction of diverse expert knowledge.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Franck Romuald Fotso Mtope, Sina Joneidy, Diptangshu Pandit, Farzad Rahimian, *Multi-Aspectual Knowledge Elicitation for Procurement Optimization in a Warehouse Company*, pp. 368-379, DOI 10.36253/979-12-215-0289-3.36

2. RELATED WORK

2.1. Human Involvement in Machine Learning Workflow

In recent years, there has been a growing interest in human involvement in the machine-learning workflow. The use of human-in-the-loop techniques has been proposed to improve the performance and reliability of machine learning models. Several studies have investigated how human expertise can be used to improve the performance of machine learning models.

In the field of data science, (Wang et al., 2021) introduced AutoDS, an automated machine learning system that aims to support data science projects by automating tasks such as data exploration, model training, and model selection. This system proposes suggestions (ML configuration, pre-process data, etc.) to the users via a web-based graphical interface where they can interact and make amendments. They showed that the proposed system improved the productivity of ML workflow while delivering better models.

In the field of aerospace systems, (D'Angelo & Palmieri, 2020) proposed the use of genetic programming to extract knowledge from aerospace structural defects by providing a mathematical model of the defects, which can be used for recognizing other similar ones. They found that their approach was effective in building reliable models of the defects and can be considered a successful option for building the knowledge needed by tools for controlling the quality of critical aerospace systems.

(Sundin et al., 2022) proposed a principled approach to use human-in-the-loop machine learning to help chemists adapt the multi-parameter optimization (MPO) scoring function to better match their goal. They proposed a method that uses a probabilistic model that captures the user's idea and uncertainty about the scoring function and uses active learning to interact with the user. They showed the effectiveness of their approach in two simulated examples achieving significant improvement in less than 200 feedback queries.

Overall, these studies demonstrate the potential of a human involved in the ML workflow to improve the performance and reliability of machine learning models. However, further research is needed to understand the best ways to incorporate human expertise into the machine-learning process, and how to effectively balance the trade-offs between automation and human involvement.

2.2. Fusion-driven learning

The fusion-driven learning consists of the fusion of knowledge experts with data collected from other sources to improve the performance of machine learning models. Indeed, several works have been introduced to leverage the strengths of both human expertise and data-driven methods to create more accurate and reliable models. The most representative works are discussed hereafter (Ademujimi & Prabhu, 2021; Ben Brahim et al., 2022; Hu et al., 2019; Huang et al., 2019; Lee et al., 2020; Seymoens et al., 2019).

(Huang et al., 2019) propose a hybrid approach for identifying the structure of the Bayesian network (BN) for the threat assessment of mass protests. They demonstrate that traditional methods for discovering BN structure from data or experts were inadequate, and instead proposed a hybrid approach (ISM-K2) which enhanced the BN structure learning methods via a knowledge elicitation method called ISM (Interpretive Structural Model).

(Ademujimi & Prabhu, 2021) introduced a method for fusion-learning of Bayesian network (BN) models for fault diagnostics. They proposed an approach for expert knowledge elicitation of the BN structure aided by logged natural language data and sensor data. They found that the resulting fused BN model improved diagnostics as it had a wider fault coverage than the individual BNs.

(Hu et al., 2019) developed a methodology that combines sensor data with domain expert knowledge to improve energy fault detection. The proposed methodology includes an engagement process with experts in the energy system field to identify relevant data, an integration of domain knowledge with sensor data, an automatic selection of potential input data, and the use of machine learning to automatically build a data-driven fault detection model.

(Lee et al., 2020) presented an interactive machine-learning approach to improve the assessment of rehabilitation exercises by integrating a data-driven model with expert knowledge. This approach uses reinforcement learning to identify the most salient features of the exercise motions and generates a user-specific analysis to elicit feature relevance from a therapist for a personalized rehabilitation assessment. This study improves the performance of predicting assessment and demonstrates how machine-learning models can improve with expert knowledge for personalized rehabilitation assessment.

Overall, these studies demonstrate the potential of fusing knowledge from experts with data collected from other sources to improve the performance of machine learning models. However, further studies are needed to find techniques and methods to easily and efficiently fuse data used to train ML models while achieving the best performance.

2.3. Knowledge Elicitation Methods

There have been several studies in the past that have aimed to improve the efficiency and effectiveness of machine learning models through the incorporation of expert knowledge. These studies (Afrabandpey et al., 2019; Campos et al., 2018; Cheung et al., 2011; Crerie et al., 2009; El-Assady et al., 2020; El-Assady et al., 2019; Mantik et al., 2022; Možina et al., 2018; Park et al., 2021; Yazici et al., 2022; Young et al., 2022) have proposed various methods for extracting and utilizing expert knowledge: active learning, process mining and decision mining, and human-in-the-loop approaches.

One widely used approach is active learning, where a model is trained on a small initial labelled dataset and then iteratively queries the expert for labels on the most uncertain samples. (Možina et al., 2018) propose a data-driven tool for the semi-automatic identification of typical approaches and errors in student solutions for a programming course. They used the argument-based machine learning (ABML) method, which interactively exchanges arguments with an expert until the model is good enough. Similarly, (El-Assady et al., 2019) present a framework that integrates speculative execution, allowing users to preview the potential consequences of their actions with the model and make more efficient decisions.

Another approach uses process mining and decision mining to identify operational processes, viz., business rules. Indeed, (Campos et al., 2018) applies a decision-mining technique in an event log of a real company to discover tacit decisions that could be translated as business rules. In the same way, (Crerie et al., 2009) relies on process mining and data mining techniques to extract two sub-types of business rules: condition action assertions and authorization action assertions. Likewise, (Alkofahi et al., 2022) introduces a method to elicit business rules from real-world web applications; these rules are defined as one-to-one and one-to-many implicit dependency relations, thus minimizing the negative effect of substitute relations in decision-making.

A third approach relies on the concept of human-in-the-loop, (Afrabandpey et al., 2019; El-Assady et al., 2020; Park et al., 2021) whereby human experts are added into machine learning pipelines, allowing them to provide feedback or guidance at various stages of the model development process. For instance, (Park et al., 2021) describe a framework called "Ziva" that guides domain experts in sharing their knowledge with data scientists for building natural language processing (NLP) models. (Afrabandpey et al., 2019) introduce a method to elicit expert knowledge about pairwise feature similarities and use sequential decision-making techniques to minimize the effort of the expert while improving the prediction performance on a small dataset. (El-Assady et al., 2020) has developed a framework allowing users to provide semantics of their knowledge, which will contribute to topic model refinement.

Finally, (Yazici et al., 2022) performs knowledge prioritization after the elicitation from domain experts. The authors use knowledge elicitation and feature selection techniques to identify the most prevalent tacit knowledge variables, which are then prioritized using machine learning methods and the fuzzy Analytic Hierarchy Process (AHP).

Overall, various studies have proposed methods that allow the intuitive extraction of knowledge from experts and train optimized machine learning models. Although these methods allow knowledge elicitation, there are several areas and aspects that have not been (or have been poorly) considered so far. In this work, we aim to introduce a framework that considers the multi-aspect of concepts defining the context, their interdependence and translation into tailored specifications.

3. METHODOLOGY

3.1. Multi-aspectual Knowledge Elicitation (MAKE)

MAKE, multi-aspectual knowledge elicitation, developed by Winfield (Winfield, 2000) for planning and building knowledge-intensive systems, is based on Dooyeweerd's aspects (Table 1). By guiding and stimulating the participants to identify aspects that are important to their situation and opening up their constituents, MAKE begins with the most obvious aspects and gradually uncovers the relevance of each. As Winfield (Winfield, 2000) found, MAKE stimulated the participants to consider broader issues, lay participants were able to grasp the meaning of aspects and work with them during analysis, and some tacit knowledge was explicated through MAKE.

(Winfield, 2000) developed two visual tools to help multi-aspectual analysis. One employs a flexible mind map to build up an understanding of inter-aspectual relationships. The second method employs the Christmas Tree, designed to provide an overall picture of areas of concern that emerge during discussions. Any significant positive or negative repercussion that emerges can be 'hung on' the tree at the aspect in which it is meaningful, with the positive on one side and the negative on the other. As the picture develops, patterns emerge showing areas of significant benefit or problems, which can be clarified and tackled during the design and development process.

3.2. Proposed Framework

The framework in (*Fig. 1*) relies on the 15 aspects of Dooyeweerd (Basden, 2011) (*Table 1*) used in MAKE (Winfield, 2000) to elicit knowledge from domain experts through interactions, which allows an understanding of what is meaningful to them. Indeed, it uncovers the elements that are often not immediately apparent but contribute significantly to overall technology acceptance and success while avoiding unintended consequences. Our proposed framework consists of five key steps.

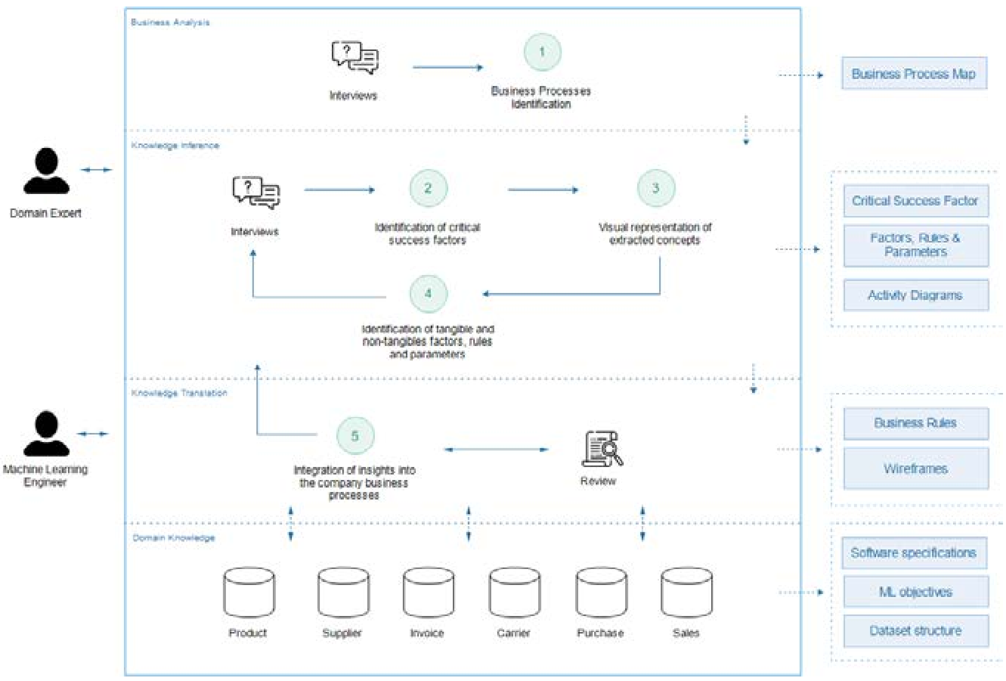

Fig. 1: Overview of the proposed Multi-Aspectual Knowledge Elicitation framework.

Table 1: fifteen aspects of Dooyeweerd (Basden, 2011) and their meaning

Aspect	Meaning
Quantitative	Discrete amount
Spatial	Continuous space
Kinematic	Movement
Physical	Energy + mass, forces
Biotic/Organic	Life functions + organisms

Sensitive/Psychic	Sense, feeling, emotion
Analytical	Distinction, conceptualization
Formative	Achievement, construction, history, technology
Lingual	Meaning carried by symbols
Social	'We': relationships, roles, convention
Economic	Frugal management of resources
Aesthetic	Harmony, play, enjoyment
Juridical	Due: responsibilities + rights
Ethical/Attitudinal	Self-giving love, generosity
Pistic/Faith	Vision, aspiration, commitment, belief

(1) Identification of business processes: analyse the company's internal/external processes to identify multiple cross-functional processes, data points, systems, and non-value-added operations. This step is essential to the identification of key data feeds (internal/external) favourable to the collection of intelligence to guide decision-making.

(2) Identification of critical success factors: gather insight from senior members and staff users of the company to understand the business and contextual issues. This step relies on a series of interviews where the discussion could turn around topics like system usefulness, job security, the impact of the technology on users and their work, user's attitudes to technology, skill levels and other factors that are meaningful to users.

(3) Visual representation of extracted concepts: take concepts from step (2) and map them against Dooyeweerd's aspects (e.g., technical, social, economic, ethical, etc.) to identify any gap or missing concept that will require further investigations (or interviews). The visual representation of extracted concepts highlights any laws, axioms, data, definitions and constraints that apply to the domain of the project.

(4) Identification of tangible and non-tangible factors, extra meta-level rules and parameters: provide a domain conceptualisation and presentation to an expert including different aspectual views to select the aspectual view(s) in which experts see their domain expertise lying. This step goes through the loop of detailed knowledge acquisition to identify business process workflows and decisions making scenarios.

(5) Integration of insights into the company business processes: propose a specification and design of the software solution to be integrated in the company information system to improve and overcome the existing limitations or challenges.

3.3. Knowledge Elicitation: application

The proposed framework relies on a series of interviews with domain experts or managers who have strong knowledge and understand the business processes. The application of this framework to a business starts with "Tutorial" interviews (Winfield, 2000), where the expert is asked to prepare a talk outlining the whole domain. , This helps provide an orientation to a domain and the identification of relevant concepts. The interviews are carried out with senior managers or team leaders who can explain the daily activities to a non-expert interviewer. As a result of these interviews, the interviewer should come up with internal/external processes which can impact the company's objectives.

The next step of the framework aims to identify critical factors which contribute to the success of the business processes. To achieve this, a "Focused" interview (Winfield, 2000) is carried out between an interviewer (ML Engineer) and domain experts to extract more detailed knowledge. This interview consists of three parts. First, there is an introduction where goals are explained to encourage the expert to take part in the discussion. Secondly, a set of topics is carefully chosen regarding previously identified concepts. These topics guide the interviewer to identify what is meaningful for experts (future users). Finally, the interviewer needs to evaluate and summarise the elicited knowledge before the interview ends.

The concepts, collected during the Tutorial interviews and Focused interviews, are mapped against the fifteen aspects of Dooyeweerd (Basden, 2011). Indeed, it consists of the analysis of each concept to determine if it can be defined or interpreted by these aspects. A set of keywords can be considered as references when analysing each concept. A keyword can represent an entity, a process, a task, or a system. As a result, the elicited knowledge can be visually illustrated and structured with the following parameters: laws, axioms, data, definitions, and constraints.

After the extraction of knowledge, the latter needs to be conceptualised to the domain and presented to an expert for validation. This step helps narrow down the knowledge and identify tangible & non-tangible factors, rules and constraints involved in the decision-making process. If the validation failed, the ML engineer needs to organize new interviews to clarify the misalignment or collect what is missing from the expert's knowledge.

Finally, the ML engineer relies on elicited knowledge to propose an ML design: dataset structure (features and observations) and the training objectives. Indeed, it helps in the creation of a multi-variant dataset that was used to train a time series model for stock forecasting purposes. Moreover, the collected knowledge guides the definitions of specifications for the software development part of the project. Indeed, it shaped the definition of models, database tables, workflows and wireframes (UX/UI).

4. RESULTS & EVALUATION

4.1. Case study

In this study, we worked with a wholesale company specializing in food export and distribution across the North UK. It operates in a multi-disciplinary environment, where teams from different disciplines work together to achieve the company's objectives. The company has several business processes, such as sales, procurement, logistics, accounting, warehouse, e-commerce, etc. that guide its daily activities and contribute to its success.

In a warehouse context, a procurement is a business process that involves identifying and selecting suppliers, negotiating contracts, and managing the purchase of food items to maintain inventory levels, meet customer demand and optimize costs. We applied our proposed method to the procurement business process, where we extracted knowledge from the team members and design machine learning models. The data and knowledge collected from the company's operations were used to train ML models, which were then deployed to support the procurement process.

Moreover, the company owns a bespoke resource management platform that supports various operations such as raising and amending purchase orders, stock management, goods-ins and quality control. The trained ML models were integrated into this platform to support the procurement process while offering a technology acceptance by the staff and final users.

4.2. Procurement: Elicited Knowledge

(1) Identification of business processes: the company's business model involves several processes, from ordering to delivery, which aims to meet the supply-demand needs. Interviews have been conducted with the company staff to better understand the existing processes and come up with a supply chain map (Fig. 2).

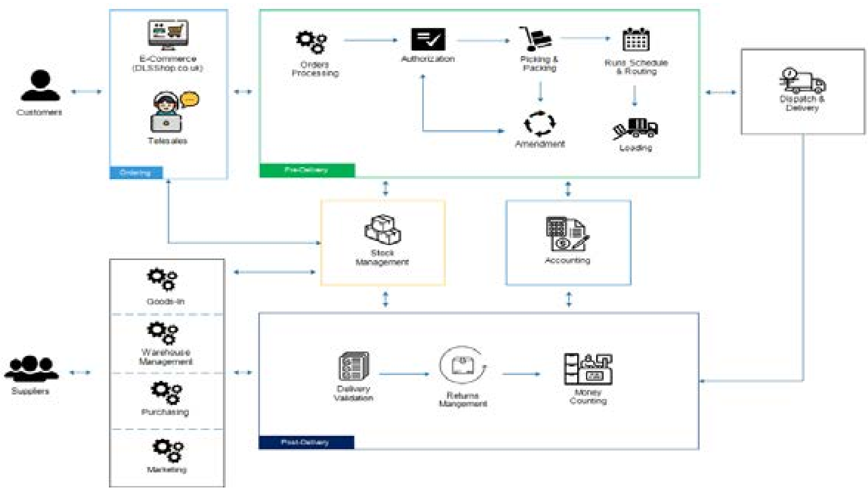

Fig. 2: Supply Chain Map

(2) Identification of critical success factors: we selected the characteristics/factors that will contribute to the technology acceptance of the new artificial intelligence (AI) platform with regards to the procurement business process.

(3) Visual representation of extracted concepts: several concepts have been identified during the interviews with the domain experts. From the procurement concept, we investigated and captured knowledge in terms of laws, axioms, data, definitions, and constraints. The following keywords have been selected as reference for our investigation: product, supplier, purchase manager, carrier, reference for quotation (RFQ), purchase order, manufacturing, delivery, return, and credit note. Table 2 illustrates the knowledge elicited from the entity "Product" and mapped against the 15 aspects of Dooyeweerd.

(4) Identification of tangible and non-tangible factors, extra meta-level rules and parameters: following the mapping of the key business processes against the Dooyeweerd's aspects, we identified data attributes and workflows required to design a ML solution. Indeed, the work sessions with experts from the procurement domain allow us to come up with tacit knowledge that is illustrated in an activity diagram (Fig. 3)

(5) Integration of insights into the company business processes: the knowledge elicited from previous steps allowed us to gather all specifications required to properly design databases of micro-services that will be part of a new software architecture in the company. Moreover, the extracted knowledge allows us to create interface insights (wireframes) illustrating each activity of the business process. Indeed, these wireframes (Figure 4) allows us to quickly validate our understanding of the business processes and ensure the technology acceptance of the future users.

Table 2: Multi-aspectual knowledge elicited from an entity "Product"

Laws	Axioms	Data	Definitions	Constraints	Aspects
Weights and Measures Act 1985	A product must have a measurable quantity	Product quantity, size, weight, cost price, sales price, online price, online offer price, collection price	A product has properties which can take a discrete amount: quantity, size, weight, price	A product should fit with the warehouse shelves dimensions/capacity	(1) Quantitative
Food Safety Act 1990 (Food Safety Act 1990)	A product must have a physical presence in a specific location	Product dimensions, location	A product has a shape, position,		(2) Spatial
Organic Products Regulations 2009 (*The Organic Products Regulations 2009*), Food Safety Act 1990 (Food Safety Act 1990)	A product must be kept in a suitable environment with respect of the shelf life	Product expiration date + Shelf life	A product has a life function	A product needs to be sold before the expiration date. A product expiration date needs to fit with the shelf life	(5) Biotic/Organic
General Food Law Regulation	A product must be stored and transported under conditions that	Product temperature, humidity and light	Product can be touched, smelled & tasted		(6) Sensitive/ Psychic

(EC) No 178/2002	maintain its sensory quality				
Food Safety Act 1990 (Food Safety Act 1990)	A product must be analysed and evaluated for its chemical and physical properties	pH, nutritional content, shelf life	Product can be distinguished	A product must have a set of chemical and physical properties	(7) Analytical
Food Standards Act 1999	A product must be capable of undergoing processing or transformation	Product Package	Some product packages are designed to meet customer expectations	Product rebranding designing should fit with each market segment	(8) Formative
Food Safety Act 1990 (Food Safety Act 1990)	A product must meet industry standards and regulatory requirements for labelling	Product name, description, code	Product labelling using symbols	Product name & code need to follow standards (length, symbols, languages)	(9) Lingual
Sale of Goods Act 1979 (Food Safety Act 1990)	A product must be priced in a manner that reflects its value	Product margin benefits, profitability and growth	Product has a limited value	Product has to be managed with frugality	(11) Economic
Food Standards Act 1999	A product must be consistent with customer preferences	Customers reviews, feedbacks	Product has to bring joy, fun, and harmony to customers	A product needs to satisfy the customers so that they get values for what they pay for	(12) Aesthetic
Food Safety Act 1990	A product must comply with relevant laws	Product reward, recompense	Product has to bring justice	A product needs to be sold in a fair ways	(13) Juridical
Food Safety Act 1990	A product must be produced and marketed with respect of ethical principles	Product advantages, benefits	Product can be beyond the imperatives	A product can be delivered earlier, discounted	(14) Ethical/Attitudinal
Food Safety Act 1990	A product must be produced and distributed with respect of spiritual and cultural beliefs	Dietary restrictions, consumer preferences	A product follows a commitment and trust	A product needs to be trustworthy	(15) Pistic/Faith

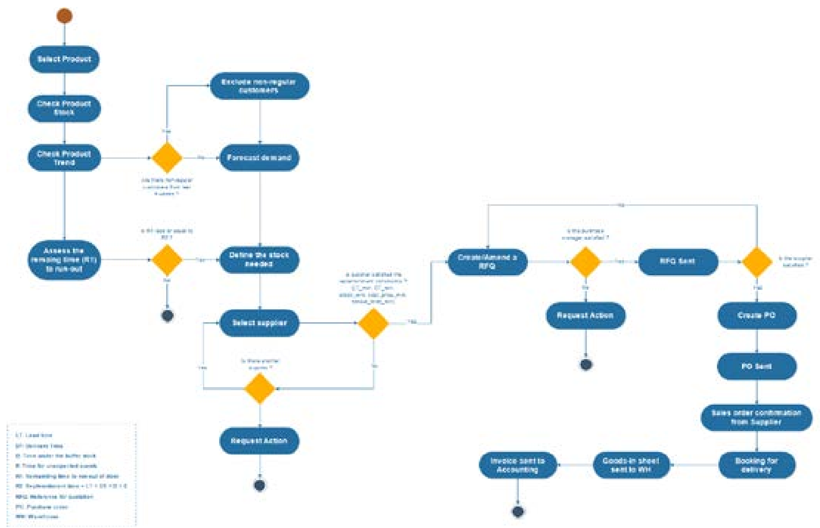

Fig. 3: Activity Diagram – Make a purchase order

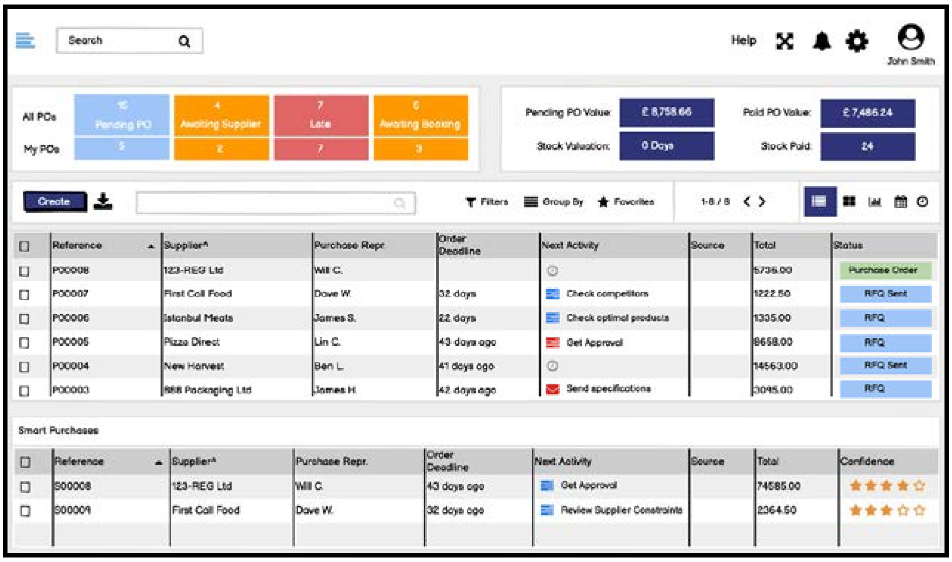

Fig 4: Procurement (Purchasing) module: this wireframe shows a quick representation of the overview page.

4.3. Evaluation of the results

The proposed framework was evaluated in a real-life warehouse environment where knowledge have been extracted from procurement experts and used to build historical sales datasets. These datasets were used to train time series forecasting models that optimize the procurement business process. We conducted the evaluation in two ways: a quantitative analysis and a qualitative analysis.

Quantitative analysis: to quantify the performance of the proposed method, we conducted a series of experiments which consists of training stock forecasting models using the datasets generated from historical sales data. These datasets were also enriched with knowledge elicited from procurement experts using our framework. These methods helped to identify the learning objectives and the representation of the dataset (features, observations, etc). We used two time series forecasting methods like ARIMA (Harvey, 1990) & TFT (Lim et al., 2020) from the literature to illustrate how our framework contribute in improving the performance of the models. To evaluate the performance of our models we used the following metric: Quantile loss (Wen et al., 2018). Table 3 shows the performance of the models trained on a dataset without elicited data (D1) and a dataset with elicited data (D2).

Table 3: Comparison of models trained on two datasets, without (D1) and with elicited features (D2), w.r.t a 0.5 percentile quantile loss (p50 loss) and 0.9 percentile quantile loss (p90 loss)

Datasets	Elicited Features	Model	p50 loss	P90 loss
D1	-	ARIMA	1.9929	1.9451
D1	-	TFT	0.6138	0.4266
D2	**Yes**	**TFT**	**0.5825**	**0.3780**

Each dataset has the following settings: 513484 time points (about 2 years of sales data), 30 days' horizon, and the stock quantity as the target feature.

Moreover, we did a comparison of models trained on datasets, which involved features extracted with knowledge elicitation techniques considered as baselines (ABML, IHTM, Ziva). We used the same time series-forecasting model (TFT) to ensure a fair comparison (Table 4).

Table 4: Comparison models trained on datasets generated with our proposed knowledge elicitation framework against baselines.

Datasets	Elicited Methods	Model	p50 loss	P90 loss
D2	IHTM	TFT	0.6827	0.4702
D2	Ziva	TFT	0.6764	0.4629
D2	**Ours**	**TFT**	**0.5825**	**0.3780**

Qualitative analysis: In order to evaluate the technology acceptance of solutions developed using our knowledge elicitation framework, we selected seven participants. This group included three individuals without prior knowledge in procurement and four members of the procurement team. The main objective was to determine whether the trained models effectively optimized business processes while considering the needs of the end user. Each participant was tasked with creating a purchase order on the system while adhering to two key constraints: avoiding stock shortages and preventing overstocking. The participants were instructed to evaluate the system based on several criteria, including user experience (UX), user interface (UI), workflow simplicity, and knowledge awareness. They rated the system on a scale of 0-5 (bad to good) for each criterion.

In terms of user experience (UX), feedback from seven participants revealed a generally positive response to the system for creating or modifying purchase orders. Five participants rated the experience with a score of 5 out of 5, indicating satisfaction, while two gave a score of 4, suggesting a desire for added features like shortcuts. Regarding the user interface (UI), six participants praised the new design with a score of 5, although one participant gave a score of 3 due to colour preferences. Evaluating workflow simplicity, three participants without procurement expertise rated it 4 for ease of following step-by-step instructions. In contrast, four procurement team members rated it 5 for consistency and accuracy. In terms of knowledge awareness, four participants rated it 5 for facilitating decisions on quantity, delivery, pricing, and supplier selection, while three desired more empirical data to bolster the system's recommendations.

5. CONCLUSION

In this paper, we proposed a multi-aspectual knowledge elicitation framework (MAKE4ML) for optimizing business processes through the design of machine-learning models. Our approach involves conducting interviews with domain experts and parameterize machine-learning models that can reproduce the expertise of the experts and provide insights for decision making. We applied the proposed framework in a food warehouse company to optimize the procurement process, resulting in a significant improvement in the accuracy of forecasting.

This framework allows us to extract concepts that were relevant to the business and useful to optimize the learning objectives of the machine learning models. Our approach can be extended to other business processes, enabling efficient knowledge elicitation, and contributing to the design of machine-learning models that can optimize operations, reduce costs, and increase efficiency.

Furthermore, we plan to investigate the combination of multi-aspectual knowledge elicitation techniques with the active learning. Active learning has been shown to be effective in reducing the amount of labelled data required for training machine learning models. We believe that combining active learning and the multi-aspectual knowledge elicitation technique MAKE4ML can lead to even more efficient and effective optimization of machine learning models.

Overall, our multi-aspectual knowledge elicitation framework can be a valuable tool for optimizing business processes through the design of machine-learning models. By leveraging the knowledge and expertise of domain experts, we can develop more effective machine learning models that can lead to cost savings, improved efficiency, and better decision-making. We hope that this paper provides a valuable contribution to the field and inspires further research in this area.

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A SYSTEMATIC LITERATURE REVIEW TO IDENTIFY A METHODOLOGICAL APPROACH FOR USE IN THE MODELLING AND FORECASTING OF CAPITAL EXPENDITURE OF HYPERSCALE DATA CENTRES

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ABSTRACT: *The theme of 'Managing the digital transformation of the construction industry' emphasises the importance of considering various dimensions of digitalisation and optimising the built environment. This review aims to present methodological approaches from existing literature that elucidate location-related factors impacting the capital cost of data centres. These findings facilitate adjustments to historical cost data when estimating total costs for new data centres. A systematic literature review method was employed to ensure an objective and comprehensive synthesis. In conjunction with Bayes's theory, this review identifies that a Delphi methodology is the most suitable methodological approach for forecasting and modelling capital expenditure for hyper-scale data centres. The methodology enables collective decision-making and consensus building, recognising the stakeholder's pivotal role in shaping the future of data centres. These findings offer valuable insights for researchers and practitioners in forming a methodological approach for further investigations into the location-related factors impacting the capital cost of data centres. Embracing this knowledge allows us to align research and practice, ensuring that these practices become integral to shaping the future of data centres and the digitalisation and optimisation of the built environment.*

KEYWORDS: *cost; decision analysis; forecasting, data centres*

1. INTRODUCTION

The rapid expansion of digital technologies requires buildings (called Data centres) to house information technology (IT) equipment to store and process data and services required by digital transformation, including the internet. Due to the advantages such as advanced technological progress in the sector and the cold climate conditions, certain regions of the world, such as the Nordic regions, are preferred by investors to build Data centres. This presents unprecedented challenges to construction cost consulting professionals in providing reliable capital cost estimates as early as a potential (international) location is identified. In the very early stage of a project opportunity, cost consultants provide capital expenditure input to support development appraisal exercises which estimate the residual land value and input to the Order of Cost estimate involved 'in determining the possible cost of a building(s) in relation to the employer's fundamental requirements' (RICS, 2013).

As these activities occur before preparing a complete set of working drawings (RICS, 2013), capital expenditure is estimated by benchmarking cost data from previously completed similar projects. This involves comparing and contrasting the difference between historical and proposed projects concerning the cost-significant variables such as location, building size, market conditions and their impact on capital expenditure. Existing literature reveals generic cost modelling approaches that could be used in early cost estimates and details of cost-significant variables that need to be considered during cost modelling (Parameswaran et al., 2019; Hashemi et al., 2020).

However, as data centres are relatively new to the construction sector and their design and construction significantly depend on the location (King et al., 2023), the suitability of the generic cost modelling approaches has yet to be widely investigated. Therefore, particularly regarding the conference theme and the growth of the internet, more research is required to establish the impact of site location on the capital expenditure of hyper-scale data centres; this will assist in selecting the correct location to make informed decisions and reduce the financial risk and contingency estimate to ensure a more accurate construction cost. This paper aims to present findings of a systematic literature review to determine the theoretical and methodological approaches in existing literature concerning the location-related factors affecting the capital cost of data centres that could be used to adjust historical cost data during their use in estimating the total cost for new data centre projects.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
David King, Nadeeshani Wanigarathna, Keith Jones, Joseph Ofori-Kuragu, *A Systematic Literature Review to Identify a Methodological Approach for Use in the Modelling and Forecasting of Capital Expenditure of Hyperscale Data Centres,* pp. 380-387, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.37

2. MATERIALS AND METHODS

2.1 Approach

A systematic approach has been used to identify and synthesise the literature results to ensure an accurate, unbiased synthesis. It is an approach where literature on a complex topic has been conceptualised and studied differently among researchers (Greenhalgh et al., 2005). This review identifies methodological approaches, geographies, historical development, quality, and literature validity.

2.2 Scoping Strategy

The literature search strategy utilised a scoping review based on that as derived from PRISMA (Tricco et al., 2018) and to provide rigour to justify further research (McInnes et al., 2018). The search strategy used the advanced search tool with Boolean keyword operators. In total, 1,375 studies were identified. After an initial review of the abstract of the papers, 508 were identified as being focused on construction, data centres and cost variables. From those identified as suitable, 87 were identified as duplicated, reducing the number of papers for review to 421. As Suarez-Almazor et al., (2000) suggested, it is vital to utilise a second database to identify potential inconsistencies. In addition, it may further enhance and support the literature review with newly identified literature. Using the same search criteria as the stage 1 search, a further 1,623 studies were identified; after an initial review of the abstract of the papers, 402 were identified as being focused on construction, data centres and cost variables. From those identified as suitable, 251 were identified as duplicated from the initial stage 1 search, further reducing the number of papers for an abstract review to 151, bringing the total for abstract review to 572. Following an abstract and full text review a total of 161 studies were selected for final review, as Figure 1.

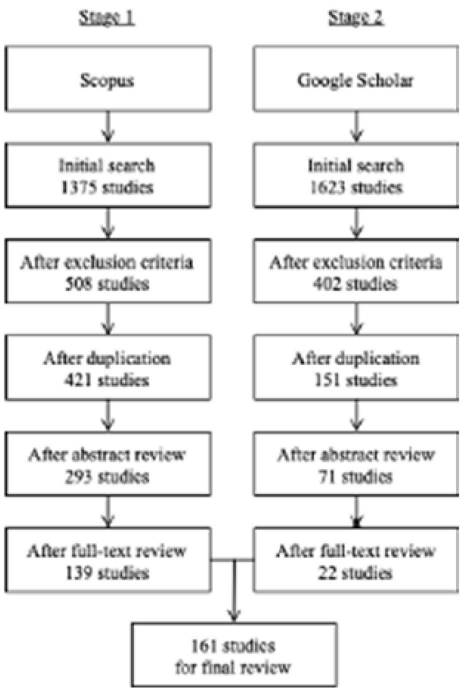

Fig 1. Systematic approach for literature

2.3 Validity and quality of literature

To assess validity and quality, the papers have been analysed and identified against peer-reviewed literature and grey literature, as it is recognised that the inclusion of grey literature in systematic reviews provides rigour and balance of recognised sources of information (McAuley et al., 2000; Blackhall, 2007). Whilst grey literature means many things to many people (Mahood et al., 2014), this review identifies grey literature as being book chapters, conference proceedings and trade publications. According to McAuley et al., (2000), the review process for a meta-analysis should strive to locate and incorporate various reports, including both published and grey literature, that satisfy pre-established criteria for inclusion. In our systematic literature review, we comprehensively searched literature and identified 161 papers for final review. The review process assessed the literature's validity and quality, including both peer-reviewed and grey literature sources such as book chapters, conference proceedings, and trade publications as identified in Table 1. We found that 84% of the selected literature was peer-reviewed journals, while the remaining 16% comprised other sources.

Table 1. Sources of literature

Source	Frequency	% of total
Book Chapters	9	6%
Conference proceedings	10	6%
Peer reviewed journals	136	84%
Trade publications	6	4%
Totals	161	100%

3. RESULTS AND DISCUSSION

3.1 Methodological Approaches to Cost Modelling

To fully understand the methodological approaches utilised in research, provide data on their use by researchers in previous studies; this identifies the approach taken in each study for synthesising the data that may be useful for future studies. Analysing the abstracts identified methodological approaches in the selected literature from the scoping strategy; this meta-narrative has shown that the prediction method has the highest count across all sectors. The prediction method has been used significantly in modelling data centre costs. The other vital approaches include machine learning, heuristic, stochastic method, parametric modelling, AHP, Regression Analysis and Monte Carlo simulation. It is worth noting that some papers identified Machine Learning, and some artificial neural network techniques, whilst others used neural network techniques. Due to the similarity of the techniques and neural networks forming a subset of machine learning, we have grouped these in the Machine Learning category. Likewise, several papers identified similar techniques whilst others identified heuristic techniques; again, we have grouped these in the heuristic category due to the similarity of these techniques.

When analysing what methodological approaches are specific to the data centre sector by eliminating other construction sectors resulting from the scoping search, the results identified 59 different approaches related to data centres. These results demonstrate that prediction methodology holds the highest vote count. This methodological approach aligns with the vote count trend for the prediction method. It is acknowledged that prediction theory is not an absolute exact science and 'can be compared to weather forecasting, stock market predictions or 'betting on how fast a 100-meter foot race will be run' (Line, 2008). Prediction theory also requires a substantial quantity of data to enable prediction. Advanced modelling techniques are extensively used in cost modelling to improve accuracy. One of the most recent advancements in Machine Learning-based approaches. According to a recent systematic review (Hashemi et al., 2020), ANN and Regression Analysis were identified as the most widely used ML-based cost modelling techniques, followed by hybrid models such as ANN with fuzzy logic, CBR and GA (Genetic Algorithm). Machine Learning involves developing a machine-based system that can learn from data. A large volume of historical data is paramount for a machine-learning model.

As data centres are relatively new, developing a machine learning-based model is not feasible at this early stage when historical cost data is limited. Fazil et al., (2021) demonstrate that obtaining a reasonably accurate neural network prediction is possible even when insufficient information is available during the initial design. However, Gunaydin and Dogan (2004) argue that the accuracy that a cost estimation neural network model strongly relies on the quality and quantity of data samples used. They claim that more data samples lead to less prediction error. Therefore, to create an accurate cost prediction model for building projects, it is necessary to have reliable and high-quality cost data for various types and conditions of buildings. Case-based reasoning is another potential method for cost prediction, which involves retrieving information from historical data on similar or identical cases. However, there are challenges associated with the retrieval process, such as computing similarity measures. According to Rashid's research (2017), case-based reasoning is an effective method for predicting costs as it involves analysing past cases' attributes, thereby enhancing cost prediction accuracy. However, these models mainly rely on historical cost data. In the UK, the Building Cost Information Service (RICS, 2018) offers information on construction projects and their corresponding tender prices, and cost managers use this data to estimate the cost of a building based on the cost of a similar project with adjustments to reflect any differences. However, it does not enable generalisations about the relationships between cost and significant predictors. Lowe et al. (2016) conducted a research study, creating a dependable regression cost model that can be used to estimate the construction expenses associated with a building's final account. They highlight that, aside from its practical usefulness, creating such a model serves two other purposes. First, it provides a benchmark for evaluating the effectiveness of neural network models, and second, it helps identify the variables that display a significant linear correlation with cost. However, the effectiveness of these prediction methods has its limitations.

Regression techniques require a substantial quantity of statistical information, and their precision is affected by the supposition that the independent variables are both independent of each other and normally distributed (Son et al., 2012). In contrast, according to Zhang (2003), neural networks possess a crucial benefit over regression models because they can model nonlinear connections without relying on assumptions. Regression methods demand a significant amount of statistical data, and their accuracy is influenced by the assumption that the independent variables are independent and normally distributed (Son et al., 2012). In contrast, the primary advantage of neural networks over regression models is their capacity to model nonlinear relationships without relying on any assumptions (Zhang, 2003). However, building a neural network model also requires data, and designing an optimal network structure involves a costly trial-and-error process. Therefore, according to Son et al. (2012), there is a notable need for prediction techniques that are more robust and reliable. Likewise, acquiring input data for preparing estimates can be challenging. According to Hashemi et al., (2020), in cases where the extent of the work could be better understood, it could result in inaccurate and approximate cost estimates. Whilst it is acknowledged that few studies focus specifically on selecting suitable sites for data centres (Kheybari et al., 2020), the search identified one Delphi study for data centre projects in China as a method for selecting data centres for several cities. However, the main findings identified proximity and geographical locations as having the only impact (Yang & Ye, 2011). According to King et al. (2023), in the absence of data for assessing the impact of location variables for hyperscale data centres, a consensus will need to be obtained from industry experts to obtain the data.

Whilst Delphi has the lowest vote count, as an approach to forming a consensus, Delphi is an appropriate route. This literature review has identified that utilising voting as the ameliorated nominal group technique could be an alternative use of Delphi. According to Brauers (2018), the nominal group technique may help generate ideas about objectives that could be included in an initial version of the Delphi method. This could facilitate convergence towards a final list of objectives. Whilst other top-voted methodological approaches require a substantial amount of data to establish and make predictions for capital expenditure, a Delphi study is well suited to establish consensus to identify the impact of location variables in the case of Data centres where available published data is limited. Some scholars argue that the Delphi method lacks a well-established framework (Crisp et al., 1997; Sharkey & Sharples, 2001; Broomfield & Humphris, 2001; Turoff & Linstone, 2002; Campbell et al., 2004; Hsu & Sandford, 2007).

However, Delphi could be used only to identify location-related variables impacting the capital costs of data centres. In addition, the Delphi technique can also be integrated with Bayes theory to update established opinions through the probability of arriving at different outcomes, as expert opinions are collected through a structured sample collection technique to estimate these probable outcomes. Bayesian statistics is based on the theory produced by Thomas Bayes (1763); it is characterised by a joint treatment of all quantities of interest in a statistical model as random variables. In particular, Bayesian statistics naturally incorporate the uncertainty analysis surrounding the estimates or forecasts described in terms of probability distributions, As Figure 2.

$$P(A|B) = \frac{P(A) \cdot P(B|A)}{P(B)}$$

Figure 2. Bayes theory

- P(B) denotes the prior belief (for example, the probability of occurrence of the variable, such as the probability of encountering ground conditions)
- P(B|A) denotes the level of impact should that variable occur
- P(B) denotes the new evidence

The information obtained by the Delphi study can be fed into the Bayes formula to render current outcomes based on the updated information as provided by a qualitative assessment of the perceived impact of location variables. The combination of Bayes theory and the Delphi method enhances the accuracy and decisiveness of the mathematical model when compared directly with Prediction Theory. It is worth noting that whilst most literature identifies the Delphi method as a tool for knowledge elicitation, it is in the author's opinion that Delphi is a methodological approach in its own right due to its systematic nature, potential for quantitative analysis, iterative feedback process, incorporation of expert judgment, and consideration of uncertainty make it comparable to other methodological approaches, this is also supported by the seminal work of Hasson et al., (2000). For example, while primarily used for knowledge elicitation from experts, the Delphi method is a systematic and structured approach to gathering and aggregating opinions and judgments. It involves multiple iterations of anonymous surveys or questionnaires to collect insights from a panel of experts. While other methods might use probabilistic models, statistical analysis, or simulation techniques to quantify uncertainty, the Delphi method focuses on expert consensus and convergence to address uncertainty. These different approaches to uncertainty management can be compared and evaluated based on their effectiveness and suitability for a particular cost modelling context.

To assess the validity of the findings, we analysed book chapters, conference proceedings, peer-reviewed journals and trade publications against the data centre sector and the relationship between the various methodological approaches. This indicates that 77% of the findings were from peer-reviewed journals, with 23% being from grey literature. As a further analysis, we reviewed the country of research to establish if there were any other research gaps in specific regions or countries; this highlighted that there needs to be an identified approach in the UK. Whilst the list of methodological approaches identified is informative, it is essential to highlight our study's significant contributions and novel aspects compared to previous research in the broader field of cost modelling. Unlike previous studies, our research specifically focuses on the context of data centres, a relatively new domain within the construction sector. Data centres present unique challenges due to their dependency on location factors. Therefore, our study investigates the impact of site location on capital expenditure, addressing a crucial knowledge gap in the literature and aligning itself accordingly with constructing for the future. By exploring this specific context, we provide valuable insights that can assist decision-makers in making informed choices, mitigating financial risks, and enhancing the accuracy of construction cost estimates for data centres.

3.2 Location Specific Factors

We have examined whether there is a relationship between location-specific factors and location-specific factors influencing cost models, or do cost models influence location choices? This relationship is a crucial matter of concern in the decision-making process, as it involves understanding whether location-specific factors influence cost models or if cost models influence location choices. There are two key influences, 1) The influence of location-specific factors on cost models and 2) the influence of cost models on location choices. For example, high land prices in certain areas may increase site acquisition costs, affecting the overall project budget. Similarly, regions with high labour costs may result in higher construction expenses. Additionally, proximity to reliable power sources or fibre optic networks can impact energy costs and connectivity expenses.

Understanding the influence of these location-specific factors on cost models is crucial for accurate budget estimation and financial planning during the decision-making process. By incorporating this knowledge into the cost models, stakeholders can make informed choices regarding the site location, considering the potential impact on capital expenditure. Secondly, cost models can also influence location choices for data centre projects. These cost models allow stakeholders to evaluate potential site locations' financial viability and profitability based on projected construction costs, operational expenses, and expected returns on investment. Cost models typically consider political influences, land and construction costs, energy expenses, maintenance and operational costs, taxes, and potential revenue streams (Baloi & Price, 2003). By analysing cost models, stakeholders can compare different location options and assess the financial implications associated with each choice. This analysis enables them to prioritise locations that align with their budgetary constraints and desired profitability targets. They can provide insights into the cost-effectiveness of various site locations and guide decision-makers in selecting the most favourable option. The relationship between location-specific factors and cost models in data centre construction is bidirectional. Location-specific factors influence cost models by directly impacting various cost components. Simultaneously, cost models play a crucial role in guiding location choices by providing financial insights and evaluating the viability and profitability of potential sites.

In addition, we have compared the data centre sector to other sectors, demonstrating that other sectors also consider location and location-specific factors when cost modelling. For instance, in the retail industry, location plays a crucial role in determining the viability and profitability of a store, as researchers have found that factors such as population density, income levels, competition, and proximity to transportation hubs significantly influence the cost modelling approach for retail establishments (Kerin & Harvey, 1975; Brown, 1993). Similarly, in the real estate sector, location-specific factors are vital for estimating property values and rental rates, with research suggesting that variables such as neighbourhood quality, accessibility to amenities, proximity to schools, and crime rates directly affect residential and commercial properties (Klimczak, 2010). Furthermore, in the transportation sector, location-related factors impact cost modelling approaches, such as when estimating the costs of constructing highways or rail networks, factors such as topography, soil conditions, presence of natural obstacles, and proximity to existing infrastructure play a significant role (Daniels & Mulley, 2012). These examples demonstrate that various sectors, including retail, real estate, and transportation, recognise the influence of location and location-specific factors when cost modelling.

4. CONCLUSIONS

By analysing the methodological approaches through the systematic review, we have established trends in the literature and identified what methods are being utilised together. For example, we have identified the Delphi method as a structured and iterative approach that involves collecting and synthesising expert opinions to make informed decisions. In investigating the impact of site location on capital expenditure, the Delphi method can help gather insights from a panel of experts regarding the relationship between location factors and construction costs. By utilising the Delphi method, we can tap into the collective wisdom of experts in the field and gain insights into the impact of site location on capital expenditure. The Delphi method helps to mitigate biases and provides a more comprehensive understanding of the relationships between location factors and construction costs. Likewise, Bayes's theory is a statistical approach that allows for incorporating prior knowledge and updating probabilities based on new evidence. It provides a framework to quantify uncertainty and make probabilistic inferences. Applying Bayesian theory to investigate the impact of site location on capital expenditure involves formulating and updating probability distributions based on available data and expert opinions. By applying Bayesian theory, we can incorporate prior knowledge and new evidence to quantify the impact of site location on capital expenditure. This approach allows for a more nuanced and probabilistic assessment, considering the inherent uncertainties in the relationship between location factors and construction costs. The Delphi method and Bayesian theory provide valuable tools to investigate the impact of site location on capital expenditure for hyperscale data centres.

The Delphi method leverages expert opinions and consensus-building, while Bayesian theory incorporates statistical analysis and the integration of prior knowledge and data. Combining these approaches can provide a comprehensive understanding of the relationship between site location and construction costs in data centre projects. To conclude, it has been identified through this meta-narrative analysis that the synthesis of both Delphi Methodology and Bayes Theory is a robust methodological approach to identifying the location-related factors for hyperscale Data centres where variables are not fully known. The development and growth of data centres and the result of this research are essential to how we manage the construction industry's digital transformation.

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A VALUE STREAM MAPPING APPROACH TO THE IDENTIFICATION OF LEAN MANAGEMENT OPPORTUNITIES FOR OFF-SITE CONSTRUCTION PRODUCTION: A CASE OF REINFORCED CONCRETE SLABS

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ABSTRACT: *Off-site construction (OSC), including prefabrication and Modular-integrated Construction (MiC), is gaining popularity as a school of sustainable construction methods that can improve productivity, quality, and waste reduction. However, OSC projects face challenges related to technical integration, collaboration among stakeholders, and dynamic uncertainties. As a result, high-quality standards throughout the manufacturing process of OSC products are difficult to ensure, leading to costly rework, delays, and safety issues. This paper applies a value stream mapping (VSM) approach based on lean principles to OSC production for identifying lean management opportunities for off-site construction production. The case studied in this paper is reinforced concrete slabs. First, we employed a combination of field investigations and interviews to formalize the flow of materials and information for the case. Then, VSM processed the flow for the current state map, which highlights twelve opportunities to prioritize for slab production, e.g., the adoption of digital technology (VR, BIM) in information flows. The findings in value-added activities improvement of the opportunities demonstrate the potential of lean management in the slab production case. Furthermore, the VSM approach in this paper can identify the 'wastes' in lean theory, which are the control points of OSC production, for enhancing quality, efficiency, and resource utilization. The findings contribute to the existing body of knowledge by providing empirical evidence of the VSM approach to the identification of lean management opportunities for OSC production.*

KEYWORDS: *Off-site construction, Prefabricated products, Lean management, Value stream mapping, Quality assurance, Construction industrialization, Lean construction*

1. INTRODUCTION

Off-site construction (OSC) generally involves standardizing design, manufacturing components in the factories and assembling during construction (Hosseini et al., 2018). With the upgrades of industrialization (Mitolo et al., 2021), examples of OSC are Bricks, 2D slabs, 3D volumetric, and Modular-integrated Construction (MiC). OSC is recognized as a promising school of sustainable construction methods that integrates design, production, and construction to save energy, eliminate environmental wastes and maximize the value of the whole life cycle of construction products (Li et al., 2021). In the literature, OSC is confirmed capable of improving labour productivity and product quality, enhancing energy conservation and emission reduction, thus solving prominent problems such as strengthened resource constraints and labour shortages. On the other hand, OSC also faces challenges, such as complex technical integration, collaboration of multiple stakeholders, and dynamic uncertainties (Zhao et al., 2023). Thus, OSC requires the coordination and integrated application of a wide range of multidisciplinary and inter-organizational skills.

OSC production refers to manufacturing precast construction elements in the factory, which is the most important stage for the quality assurance of products, as the construction site could be responsible for limited rework and repairs (Wu et al., 2019). Unlike traditional manufacturing factories, OSC production is a complex system involving different stakeholders and various information interactions (Khalili & Chua, 2014). Therefore, the complexity also leads to quality risks frequently occurring throughout the entire OSC products production processes, including production planning, engineering design, mould production, components manufacturing, quality inspection, storage, and loading for logistics (Lee et al., 2016). Furthermore, the connections between the stages may amplify the risks from one stage to another, e.g., deformation occurs in the moulds at the beginning of

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Zhe Chen, Zhengting Guo, Fan Xue, *A Value Stream Mapping Approach to the Identification of Lean Management Opportunities for Off-Site Construction Production: A Case of Reinforced Concrete Slabs*, pp. 388-397, DOI 10.36253/979-12-215-0289-3.38

the production will lead to defective components, but components may meet inspection requirements in the following product stage, and such mistakes can not be identified until the inspection of the finished products (Heravi & Firoozi, 2016). Therefore, systematic quality management is vital to OSC production.

Current approaches adopted in OSC production management are limited (Lu et al., 2018). For example, in the inspection process, the inspectors conducted manual spot inspection and made subjective decisions stemming from their prior knowledge in identifying products' flaws early in the production process, which inevitably suffers from labour-intensive consumption and subjectivity of opinions rather than precisely matching the substantial conditions (Xue et al., 2018). Consequently, defects are not perceived until the later stage of logistics or even the on-site installation stage (Park et al., 2013). Defects that arise during the production stage are costly for owners, contractors, and prospective clients because they are nearly impossible to chain significantly during the assembly stage.

Lean management concepts have the potential to increase quality, efficiency, and resource utilization for OSC production (Sacks et al., 2010). In lean principles, value is created by a sequence of value-adding activities. A value stream is the sequence of activities by which a company provides a product or service that delivers a specific product or service to a specific customer (Koskela, 1993). Value Stream Mapping (VSM) is an approach for illustrating the flow of materials and information in a lean manufacturing system (Ko & Kuo, 2015). It utilizes the tools and techniques of lean manufacturing to help organizations identify where waste is and, in turn, streamline the flow of production. The purpose of value stream mapping is to identify and reduce waste in the production process (Rahani & Al-Ashraf, 2012). Waste in this context is defined as any activity that does not provide added value to the end product and is often used to illustrate the total amount of waste reduced in the production process. Managers, engineers, process planners, suppliers, workers in the manufacturing industry, and customers can all benefit from value stream mapping by identifying waste and determining where to start looking for its main causes. In this way, value process mapping can also be a communication tool in linking with stakeholders of the factories (Chen et al., 2008). In general, the adoption of VSM based on lean concepts can enable the effective utilization of resources, e.g., in the automotive industry, supply chain analysis, and manufacturing industries (Rahani & Al-Ashraf, 2012).

This paper aims to apply the VSM approach based on the identification of lean management opportunities in OSC production. The objectives of the paper are: 1) To map the OSC production process; 2) To apply VSM to the map for locating the 'wastes' in the existing process; 3) To identify corresponding management opportunities for OSC production.

2. LEAN PRINCIPLES AND VALUE STREAM MAPPING

Lean manufacturing principles have been used for a long time in the manufacturing sector to boost output, productivity, remove waste, and deliver value (Sacks et al., 2020). The term "lean principle" describes the ongoing process of raising the value of a product by removing waste without sacrificing output, productivity, or quality (Koskela, 1993). Reducing non-value-added activities and achieving value-added delivery in the construction domains are the major areas of concentration for OSC. To address resource difficulties, lean principles' practices pledge to offer solutions that are lasting. Once the lean techniques were applied to the project scenarios, it became clear that significant amounts of materials were saved.

VSM is the whole of the actions—both value-added and non-value-added—currently required to move a product through the primary flows that are fundamental to every product. It is the production flow, from the raw material to the end customer, as well as the design flow, from conception to realization (Grewal, 2008). Firstly, it is a tool to identify waste and problems. It reviews operations and processes from a macro perspective, from the input-output process, and allows managers to easily identify sources of waste (excess inventory, heavy work, time wastage, handling, inspection, etc.), thus providing a scientific basis for continuous, systematic improvement. Secondly, it provides a common language. Value streams can be used as a common language for process and process improvement, making it easy to communicate between different departments. It is a method of determining and differentiating priorities for improvement, avoiding "picking the easy ones" for improvement and maximizing the return on investment. The VSM is the basis for the preparation of improvement plans and their implementation.

The integration of lean principles and OSC has been beneficial in optimizing its production processes and has recognized great potential in effectively tackling resource waste and unsatisfactory quality. As a result, numerous researchers have used VSM in conjunction with lean concepts to increase productivity and efficiency in the OSC manufacturing process as well as other areas. According to Wu and Pheng (2011), value stream mapping of precast manufacturing is essential to achieving sustainability goals. In the case of Yu et al. (2009), by applying the value streaming on a consistent work/product flow rather than on individual tasks, the delay brought on by a conflict between the predetermined schedule and the actual schedule of the complicated process of building a house can be decreased. To identify waste during the construction of concrete slabs in residential constructions, Fontanini et al. (2013) employed value spectrum mapping with lean concepts, increasing efficiency and effectiveness. However, lean principles have their roots in the manufacturing sector, where they have a mature theoretical and research base (Grewal, 2008). There is a lack of an organized framework that can be used to promote the implementation of lean manufacturing principles in the production of OSC products.

In summary, VSM indicates the key operating procedures that adds value to the targeted product. Instead of depending solely on the currently established conventional working hours, the use of VSM is combined with field study, information gathering, and interviews, capturing the flow of material and information. Cycle times, line change times, operator counts, size of batches, and quantities of semi-finished products in a process are a few of the forms of data that are capable of being exploited to analyse the lead time and added value time of the entire process. So, in addition to the VSM approach, both field research and interviews are employed in this paper.

3. RESEARCH METHODS

3.1 Case selection

The case selected in this paper is the reinforced concrete (RC) slab in the prefabricated construction. The selection was based on the product family matrix defined in the VSM approach (Fontanini et al., 2013). Usually, RC slab production accounts for >80% in both prefabricated construction and RC MiC (Loss et al., 2016), which fulfil the requirements of the product family matrix. The case factory is in Shenzhen, which has major products including various types of precast elements such as facades, partition walls, floor slabs, staircases, columns, integrated kitchens and washrooms. The involved projects include residential, commercial buildings, roads, and tunnels.

3.2 Production process mapping

The scope of activities includes added-value activities at each level, from the raw materials to the finished products, which includes conceptual design, product design, and process designs (Sacks et al., 2020). In OSC production, it is the in-factory value stream, i.e., the manufacturing stream from design to ready-to-transport stage.

In the site investigation, observations were made regarding the plant layout, the machinery used, the sequence of activities and the time taken for each activity by visiting the site and also interacting with the staff working there. The typical activities are (A) mould assembly and preparation, (B) fixing of rebars, (C) concreting and curing, (D) de-moulding and (E) transferring for storage.

Mould assembly and preparation. Casting begins with the assembling of the mould. The front-work used to pour and cast concrete is called a mould. Using overhead cranes, the mould plates are removed from the inventory area and set down on the fixed table. Using bolt and weld connections, mould assembly and preparation entails assembling the mould plates. Based on the shop drawings that the design team produced, the assembly is carried out. The timeline of the activities taking place at the mould assembly is shown in Fig.1.

Fixing of rebars. The rebars are then fixed into the mould as the following step. Cutting, bending, and forming the reinforced cage in accordance with shop drawings are all steps in the fabrication of the rebar cage. A separate reinforcing cage is created, and then it is added to the mould. The Fig. 2 is the order of activities that take place as the rebar cage is transferred to the mould.

Concreting and curing. Concreting is the following step. Before the concreting process begins, the raw materials are fed into the mixer. Both the mixing and transporting of concrete are automated and simple to use. The system of the flying bucket is employed. The Fig. 3 is a listing of activities that take place during concreting and curing.

Demoulding and transferring to storage yard. Demoulding is followed by moving the precast concrete component with a crane to the storage location. At the storage location, curing is carried out using a sprinkler system that operates for three days. The storage location keeps the finished components for further transportation. Before delivering the components to the construction site for assembly, it is important to (i) inspect the physical state of the final product, (ii) verify the important parameters, (iii)apply the proper identification markings to the elements that indicate position, individual category, weight, size, and placement in accordance with the shop drawing, and (iv) check whether the components have reached 75% of their design strength in concrete.

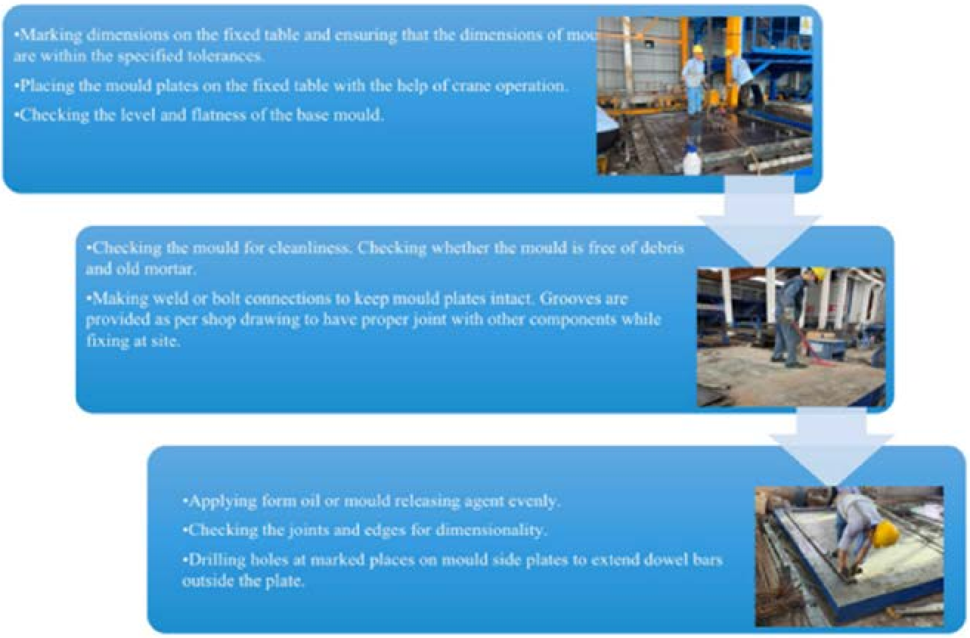

Fig. 1: Mould assembly and preparation of a prefabricated RC slab.

Fig. 2: Fixing of rebars of a prefabricated RC slab.

Fig. 3: Concreting and curing of a prefabricated RC slab.

3.3 Non-value-added activities located using VSM

This step aims to apply VSM to locate the non-value-added activities. Non-value-added activities, referred to as waste, are activities that do not directly contribute to the product's value or the customer's perception of value. These activities consume resources (time, materials, labour) but do not enhance the product or service in any meaningful way. As a result, by identifying the non-value-added activities and location of waste, the potential improvement could be a promising action. The categories and identification of non-value-added activities are listed below (table 1).

Table 1: Categories and identification of non-value-added activities.

Categories of non-value-added activities	Identification
Transportation	Unnecessary movement or transportation of materials or products between different process steps, leading to delays, damage, and increased lead times.
Inventory	Excess inventory or work in progress that is waiting to be processed, increasing capital and space without providing immediate value.
Waiting	Idle time for products, materials, or employees waiting for the next step in the process, reducing efficiency
Over-production	Producing more than what is currently needed, which leads to excess inventory and waste.
Over-processing	Performing more work than necessary, such as using high-precision processes for tasks that don't require it.
Defects	Activities required to fix mistakes, rework, or correct defects, increasing costs and schedule delays.

3.4 Identification of corresponding management opportunities

The goal of this step is to adopt VSM analysis to identify opportunities for improvement. The identifying process is based on two basic processes: the information flow and the material flow. The information flow is the process that starts when the marketing department receives an order or has already forecasted the customer's needs and makes it into a purchasing plan and a production plan. The material flow refers to the physical process, i.e., the process that starts with the supply of raw materials into the warehouse from the supplier, followed by the outbound manufacturing, the finished products into the warehouse, until the product reaches the customer. In addition, the material flow includes the inspection and storage of products. Furthermore, there are eight waste principles on which judgement is based, including waste of repair, waste of over-processing, waste of movement, waste of handling, waste of inventory, waste of making too many/too early actions, waste of waiting and waste of management. Therefore, in the analysis of this paper, any part of a product that exceeds the minimum amount of resources necessary to add value to the product is considered waste – a waste is not only an activity by definition that does not add value but also a process that overuses resources.

4. RESULTS

Fig. 4 shows the results of process mapping, the adoption of the VSM analysis for locating wastes in the current process map, and the current state map with information flow, material flow and lead time ladder. The information flow depicts the communication between the management team, the production team, the supplier, and the client. The material flow displays the movement of materials through different steps from supplier to finished product. Cycle time denotes the duration of each step, whereas lead time indicates the length of time it takes to produce precast components from an order to their completion. While cycle time solely includes time for value-added activities, lead time contains time for both value-added and non-value-added activities. The sequence of activities is named from A to E. Evidences of the current waste locating. 1) Waiting. A curing period of 12 hours is required when employing the water pond method, thereby extending the waiting duration for subsequent procedures. 2) Defects. Damage to mold plates occurred when the welded connection was disrupted during the demolding process. 3) Overprocessing. Remediation of damaged finished components was carried out through epoxy injection, thereby elongating the lead time. 4) Motion. The Reinforcement cage production area is situated 200 meters away from the molding table, resulting in an increased travel time for the crane during the transfer to the table platform. 5) Transport. The storage area for mold assembly parts is situated at a distance of 400 meters, leading to an extended travel time for the EOT crane during the transfer to the table platform.

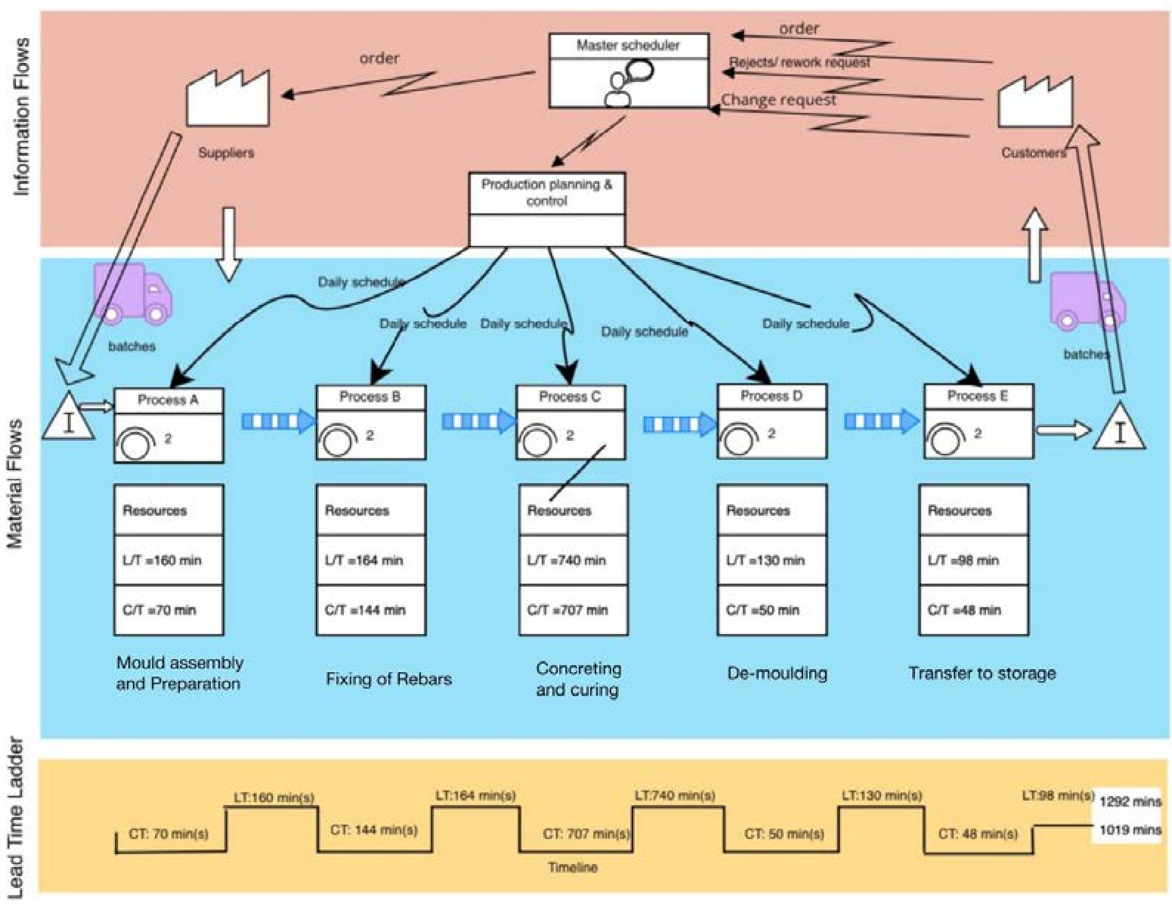

Fig. 4: VSM of the RC slab production. (Note: Process A- Mould assembly and Preparation, Process B- Fixing of Rebars, Process C- Concreting and curing, Process D- De-moulding and Process E- Transfer to storage)

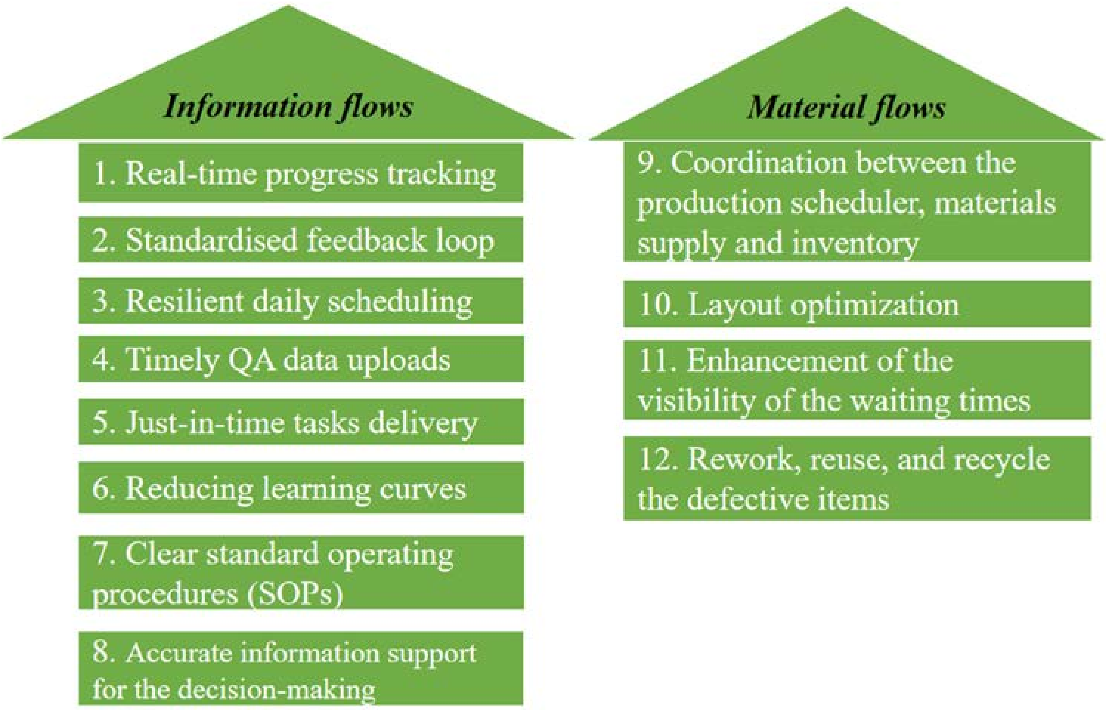

Fig. 5: 12 opportunities for potential improvement

Twelve opportunities are highlighted, as shown in Fig. 5, in information flows and material flows based on the VSM of the RC slab production. In the information flows, eight opportunities are concluded. **Opportunity 1**: real-time progress tracking, such as the adoption of Virtual Reality (VR) (Rahimian & Ibrahim, 2011) and Building Information Modeling (BIM) (Xue et al., 2021), enables the off-site production team to monitor every step of the production process as it happens. This visibility facilitates quick identification of bottlenecks, inefficiencies, or delays. With the assistance of a real-time view of progress, the stakeholders can take proactive measures to optimize workflow, allocate resources more effectively, and prevent unnecessary downtime. **Opportunity 2**: implementing a standardized feedback loop creates a systematic process for collecting insights and suggestions from various stakeholders involved in the factory. The information loop contributes to continuous improvement, as the feedback is used to identify areas for refinement and innovation. By incorporating valuable input from workers, the production process becomes more streamlined, and waste is reduced through collaborative problem-solving and optimized processes. **Opportunity 3**: a resilient daily scheduling approach acknowledges the dynamic nature of off-site construction and prepares for potential disruptions. By building flexibility into the schedule, the stakeholders can better adapt to unexpected changes without causing significant interruptions. **Opportunity 4**: timely quality assurance data uploads play a crucial role in maintaining high-quality production standards. By promptly uploading quality assurance data, any deviations or defects are identified early in the process, allowing for timely corrective actions. This reduces rework, minimizes waste associated with defects, and ensures that the final product meets or exceeds quality expectations. **Opportunity 5**: adopting a just-in-time task delivery approach optimizes the timing of task completion to match actual production needs, preventing the accumulation of excess inventory or work in progress. **Opportunity 6**: emphasizing the reduction of learning curves through proper training and skill development enhances the expertise and efficiency of the production workforce. Skilled workers are less likely to make errors or require additional time to complete tasks. **Opportunity 7**: establishing clear and well-documented standard operating procedures (SOPs) provides a structured framework for the entire off-site production team to follow. These SOPs guide consistent and standardized practices, reducing variations that can lead to errors or inefficiencies. Clarity in procedures minimizes waste associated with defects, misunderstandings, and unnecessary deviations from the optimal workflow. **Opportunity 8**: access to accurate and timely information forms the foundation of effective decision-making in off-site production execution. The reliable data leads to quicker and more confident decisions, aligning with lean principles by reducing delays and uncertainties that can lead to waste.

Four opportunities are summarized in the material flows. **Opportunity 9**: effective coordination between the production scheduler, materials supply, and inventory management is vital for lean management in off-site construction. By synchronizing production schedules with the availability of materials and maintaining an optimized inventory level, the production process could embrace increased efficiency. **Opportunity 10**: optimizing the layout of the factory is a strategic improvement opportunity that can significantly enhance lean management. By arranging workstations, storage areas, and production lines logically and efficiently, material flow is streamlined. This optimization reduces unnecessary movement, transportation, and waiting times, leading to improved overall efficiency and resource utilization. A well-organized layout also supports just-in-time delivery and minimizes the chances of defects or errors. **Opportunity 11**: increasing the visibility of waiting times is crucial for waste reduction and process improvement. By close monitoring and making waiting times transparent to all stakeholders, bottlenecks and delays are quickly identified. This visibility prompts immediate action to address issues, prevent idle time, and maintain a consistent production flow. **Opportunity 12**: the practice of reworking, reusing, and recycling defective items is a sustainable and lean-approach. Efforts are made to salvage and repurpose them where possible, leading production management to the more resource-efficient and environmentally responsible.

5. DISCUSSION AND CONCLUSION

The OSC production is that the dynamic nature of the production requires a rapid response. However, OSC production, unlike a generic manufacturing facility, has long order lead times, relies on several tiers of subcontractors and casual labours, and requires close coordination. This paper maps OSC production processes in the factory and applies the VSM approach from lean manufacturing to lean OSC management opportunities. The findings from the RC slab case demonstrate the identification of the existing wastes, non-value-adding activities, and potential lean management opportunities. Examples of the opportunities include eight opportunities in information flows and 4 opportunities in material flows.

The contribution of this paper mainly lies in advancing lean management practices in the field of off-site construction. By offering practical, and customized solutions, it is promising to drive positive changes, optimize production processes, and foster continuous improvement within the OSC production.

There are several limitations in this paper as well. First, this paper involves one typical case of RC slab without detailed analysis on the generalizability to other products. Further, VSM is a dynamic tool, and the process should be revisited periodically to ensure ongoing improvements. Future research could focus on how to apply a more scientific and rational approach to further improve the quality and management efficiency of OSC products in the identified management phases.

ACKNOWLEDGEMENT

The work presented in this paper was supported by the Shenzhen Science, Technology and Innovation Commission (SZSTI) (No. SGDX20201103093600002).

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BAYES THEORY AS A METHODOLOGICAL APPROACH TO ASSESS THE IMPACT OF LOCATION VARIABLES OF HYPERSCALE DATA CENTRES: TESTING A CONCEPT

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ABSTRACT: *The theme of 'The Impact of Engineering Practices on a Sustainable Built Environment' emphasises the importance of considering various dimensions of resilient infrastructure. Selecting the location for a Hyperscale Data Centre is a crucial process that involves assessing the impact of various location variables. To determine the viability of a location, it is essential to identify the potential risks associated with each variable. This paper presents a proprietary methodological approach that includes a Delphi study to identify risks, a Likert scoring system to assess prior probabilities, and a Bayesian theory-based decision tree to assess the impact through risk prediction. The paper's contributions are significant, and the proposed methodology makes it possible to predict the risk level of each location variable by identifying the appropriate contingency percentage. The study's findings indicate that the paper's proposed approach is an effective way to mitigate the risks associated with selecting a location for a Hyperscale Data Centre. Embracing this knowledge allows us to align research and practise with the conference's call to studying the resilience of buildings and infrastructure to natural disasters and climate change, and developing strategies for adaptation and mitigation, ensuring that these practises become integral to shaping the future of Data Centres.*

KEYWORDS: *Bayes Theorem, Delphi, Data Centre, Location Variables*

1 BACKGROUND

Investments in Data Centres in the Nordic region have been on the rise, with significant contributions from cloud and hyperscale investors such as Facebook, Google, AWS and Apple, due to advanced technological progress and favourable cold climate conditions, significantly reduce the cooling energy demands of the facilities (Christensen et al.,2018; Avgerinou et al., 2017). However, the location of Data Centres outside of the UK presents a significant challenge for cost consultants during the capital cost estimation and modelling stages, which can impact investment decisions. At the feasibility stage, cost planning involves determining the possible cost of a building early in the design stage in relation to the employer's fundamental requirements before preparing a complete set of working drawings or quantities bills (RICS, 2011) Historical cost data is often used as base cases for cost consulting professionals, who adjust their costs to suit the circumstances of new projects. Although specific characteristics such as shape, inflation, and specifications are relatively easy to adjust based on case-based reasoning, predicting the impact of location is challenging for construction professionals, who rely on location cost indices for this purpose. Various location cost indices, such as Spon's Architects and Builders Price Book (AECOM, 2017) and the Building Cost Information Service (RICS, 2018) are available for cost consultants. However, such indices are less relevant for Data Centres as there are often no precedents set to use as a baseline for cost comparisons, and there are many variables ranging from macroeconomic, construction methodology, geographical, and geological categories. For example, regulations for noise attenuation for hyper-size generators for Data Centres did not exist in Sweden and had to be modelled on regulations from other countries (Vonderau, 2017), International location cost indices, such as those provided by Eurostat (EC, 2019), World Bank (2022) and the OECD (2022) are broad and mainly model variations at the country level, making them less effective during cost planning for individual projects specific to a particular region. Therefore, construction professionals must consider multiple factors and rely on a combination of indices and expert judgment to provide accurate cost estimates for Data Centres.

2 RESEARCH AIM

Whilst a wide range of variables impacts construction project costs and cost modelling, there is no evidence to suggest whether and how these variables would affect site location in cost planning for the capital expenditure of Hyperscale Data Centres. Although there is published data on traditional construction costs and location indices in the UK, they do not provide enough information to assess the impact of location variables, especially considering the specific design requirements of Data Centres (King et al., 2023). This highlights a significant knowledge gap in the existing body of research. This paper aims to validate a methodological concept using Delphi

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
David King, Nadeeshani Wanigarathna, Keith Jones, Joseph Ofori-Kuragu, *Bayes Theory as a Methodological Approach to Assess the Impact of Location Variables of Hyperscale Data Centres: Testing a Concept,* pp. 398-406, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.39

and Bayesian theory to assess the probability and impact of location variables. This approach aims to aid in selecting the appropriate methodological approaches for the research topic of "the impact of location variables on the modelling and forecasting of Hyperscale Data Centres". By utilising this method, the study seeks to identify the potential risks and impacts of various location variables, contributing to a more comprehensive understanding of the relationship between site location and capital expenditure in the Hyperscale Data Centre industry.

3 METHODOLOGY

3.1 Risk

Risk refers to situations that involve uncertainties that may occur, risk mitigation refers to actions taken to optimise the impact of risk. By selecting a comprehensive risk management strategy that considers all types of risk, one can ensure the implementation of a planned Data Centre investment within the specified time and budget. Various organisations have developed several approaches to risk. Notable among these are the Project Management Institute (PMI., 2001) and PRINCE2 (Bentley., 2012). This paper aims to introduce a concept that can quantify the impact of risk through a Delphi and Bayesian approach. A risk is defined as the probability of an event occurring and the subsequent consequence, as expressed in Equation (1). Here, R represents a risk, P is the probability of the event occurring, and C is the impact or consequence of the event.

$$R = (P, C). \quad (1)$$

Various methodologies exist for identifying risk including identification, assessment, response, and monitoring. Risk identification is identifying potential risks that may impact the project. Risk assessment involves analysing and evaluating the likelihood of occurrence, impact, and consequences of the identified risks. The risk response involves developing a plan to manage or mitigate the identified risks. Lastly, risk monitoring and control. Quantifying the impact of risk, especially with location variables, can provide invaluable information to decision makers and stakeholders and can be used to make informed decisions, develop contingency plans, and allocate resources appropriately. Therefore, developing a method to assess the impact of location variables on project risk can significantly improve the success of a project. Risk decisions involve assessing the factors that contribute to the emergence of risk and the likelihood and potential impact of the event.

3.2 Delphi Study

A pilot Delphi study (King et al., 2023) has been conducted to obtain expert opinions on the key themes that affect the location variables of Hyperscale Data Centres and their impact on the modelling and forecasting of capital expenditure. The analysis of the pilot study data has provided rigour and validity to the questionnaire for the main forthcoming Delphi study. This has allowed for identifying and assessing potential risks associated with the location variables of Hyperscale Data Centres. The pilot study results indicate the current understanding of the variables that impact the modelling and forecasting of capital expenditure for Hyperscale Data Centres. These variables have been identified as potential risks and are an essential consideration in the risk management strategy for the planning and implementing Hyperscale Data Centres. Previous research found that pilot Delphi studies are rarely reported in academic literature, making it difficult to establish best practices (Clibbens., 2012). For this pilot study, industry expert knowledge was obtained through several expert participants (n=5). The response rate was 100%. Through an open-ended questionnaire, experts could respond freely and without restriction. Having completed the thematic analysis of the data arising from the questionnaire, the pilot study identified categories and themes that are considered risk items; the following items were among those rated by the participants as having an impact on capital expenditure when locating a data centre:

- Requirement for cooling towers due to sub-zero climate
- Requirement to import generators due to in-country shortages.
- Acoustic screens to generators due to proximity of residential neighbours
- In-country technical labour shortages require backfilling with imported, experienced technical labour.

The themes arising from the Delphi study provide the data that will be used to provide the data that will be used for the assessment of the impact of location variables within a Bayesian framework.

3.3 Bayes Theory

Bayesian theory is based on the probability theory given by Thomas Bayes in 1763 (Bayes., 1763). Bayes's theory relates the conditional probabilities of random variables to each other. It provides a framework that allows for the integration of a prior belief about the distribution of a quantity of interest (the prior distribution) and the observed data (through the likelihood term). as shown in Equation (2).

$$P(A|B) = \frac{P(A) \cdot P(B|A)}{P(B)} \qquad (2)$$

To clarify, in this instance:

- P(B) denotes the prior belief (for example, the probability of occurrence of the variable, such as the probability of encountering ground conditions)
- P(B|A) denotes the level of impact should that variable occur.
- P(B) denotes the new site-specific evidence (for example, when new information arises, i.e., a higher probability of occurrence of encountering ground conditions)

Bayes theory can be applied to numerous components by using the product rule (Pearl., 2022) and, therefore, Bayes theory is applied for calculating the probability of occurrence of a phenomenon or hypothesis using multiple factors or variables. It is also considered a powerful method for hypothesis testing (Wetzels et al., 2012) making assumptions and having wide-ranging decision-making applications related to artificial intelligence, machine learning, and bio-statistics approaches. Prediction theory is a sub-field of statistics and machine learning that involves the development of mathematical models and algorithms for predicting future outcomes or events (Sarker., 2021). It uses data from past observations to create models that can be used to forecast future outcomes. Prediction theory employs various data analysis techniques like regression, clustering, and classification. It also involves identifying essential variables and patterns within the data, calculating the probability of specific outcomes, and selecting desirable outcomes based on the model generated. Although prediction theory and Bayes theory are related, they differ in terms of their fundamental principles. Bayes's theory concerns conditional probability and allows for the revision of probabilities based on new information or evidence (Ajzen et al., 1975). On the other hand, prediction theory is focused on building models and computing algorithms to predict outcomes from complex data sets. While prediction theory may incorporate probabilities, it does not involve the revision of probabilities like Bayes's theory. Using Bayesian theory and correlation analysis is a common practice for predicting future outcomes and events. In addition, integrating prediction theory with the Delphi method is a recognised technique used to forecast future outcomes based on expert opinions (Turoff et al., 2002). The Delphi method involves obtaining consensus opinions from subject matter experts through a series of planned interviews or surveys, which can then be used to forecast future outcomes. Furthermore, the Delphi method can be combined with Bayesian theory to revise established opinions based on the likelihood of different outcomes. This study highlights that expert opinions gathered through a structured sampling technique such as the Delphi method can be utilised to estimate probable outcomes, which can then be inputted into the Bayesian formula to provide current outcomes based on updated information gathered through qualitative risk assessments. The combination of the Delphi method and Bayesian theory enhances the accuracy and decisiveness of the mathematical model compared to using prediction theory alone. Previous research supported this approach, including Bijak (2011), who identified Bayesian theory as a natural methodology for combining expertise and data with expert judgments. Additionally, Bernardo (2003) suggests that Bayes's formula allows for expert opinions to be incorporated into projections in the form of prior distributions. However, a limitation of Bayesian forecasts is that they may contain subjective elements due to their dependence on expert opinions and history obtained from the data series (Abel et al., 2013). In conclusion, the combination of Bayesian theory and the Delphi method can provide a robust methodology to model and forecast the impact of location variables on Hyperscale data centres.

4 DATA COLLECTION

4.1 Likert

Psychologist Rensis Likert invented the Likert scale (Likert., 1932). It is a rating scale used to measure attitudes, opinions, or perceptions. The scale can have anywhere from 5 to 11 points, with the most common being a 5-point scale. It is widely used in social sciences, especially in survey research, as it allows researchers to gather information about people's attitudes, opinions, or perceptions systematically and standardised. The scale is also commonly used in market research, customer satisfaction, and employee engagement surveys. The Likert scale has several advantages, including ease of use, simplicity, and flexibility. It is easily understood by respondents, which can improve the accuracy and reliability of the data collected. However, it is important to remember that the Likert scale also has limitations, such as possible response bias, limited ability to capture complex attitudes, and the potential for data to be misinterpreted if it is not used appropriately. It is important to carefully consider the wording and format of the questions in the Likert scale to minimise these limitations and ensure accurate data collection. Additionally, it is essential to use appropriate statistical techniques when analysing the data obtained through the Likert scale to avoid misinterpretation of the results.

4.2 Probability

To establish the likelihood of events, a Likert ranking has been proposed with two extremes at either end of the scale. A score of 1 denotes an event highly unlikely to occur, whereas a score of 5 represents a highly likely scenario, as shown in Table 1. For instance, when assessing power availability, one might score it as one because the likelihood of that event occurring is low. On the other hand, if there is a substation on-site and the site is situated in the centre of a seismic zone, a score of 5 may be assigned since the probability of a seismic event causing damage is very high. These scoring descriptions outline the scoring criteria and help prevent ambiguity when experts score as part of the Delphi study.

Table 1: Likert ranking for probability.

Likert scale	Probability
1	Very unlikely
2	Unlikely
3	Neutral
4	Likely
5	Very likely

The variables identified and presented in Table 2 are derived from a previous Delphi study by King et al (2023).

Table 2: Likert scoring results for the probability of the event occurring.

Variable	Very unlikely	Unlikely	Neutral	Likely	Very Likely
Cooling towers	4	1	4	41	16
Imported generators	4	4	32	23	3
Acoustic screens	4	1	4	39	18
Technical labour shortage	4	28	27	5	2

These Likert scoring values are intended to illustrate the proof of concept. They are based on the authors' professional judgment regarding the probability of each item occurring in the real world. However, it is essential to note that these scores are hypothetical for illustration only to demonstrate the proof of concept. They will be subject to revision based on new available information, resulting in updated posterior probabilities that may differ significantly from the initial estimates.

5 RESULTS AND DISCUSSION

5.1 Establishing Nodes

The scoring rankings for probability are derived from the Likert scoring results in Table 2 and weighted to generate the probability distribution required for the Bayesian analysis. A weighing method has been used to assess these conditional probabilities, as shown in Equation (3).

$$\frac{Occurance}{Total\ respondants} \qquad (3)$$

The variables and the conditional probability of these events occurring are shown in Table 3. The results subsequently creating the nodes for the Bayesian network.

Table 3: Conditional probability of the event occurring.

Item	Very Unlikely	Unlikely	Neutral	Likely	Very Likely
Cooling towers	6%	2%	6%	62%	24%
Imported generators	6%	6%	48%	35%	5%
Acoustic screens	6%	2%	6%	59%	27%
Technical labour shortage	6%	42%	41%	8%	3%

Therefore, the node describing the event of Cooling Towers together with possible scenarios of this likelihood together with possible assessment factors is as Figure 1

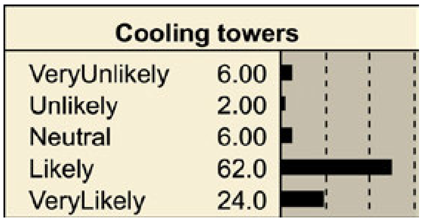

Figure 1: Conditional probability node of Cooling Towers being required.

5.2 Assigning event probabilities

A process of identifying possible events for each of the variables was established. The basis of the Bayesian network is related to determining the relationship of each individual node in the network. For this proof of concept, the relationship of individual node was based on the authors' own experience and assessed using a low, medium, and high ranking. For example, the impact of cooling towers is identified in Figure 2.

Cooling towers	Low	Medium	High
VeryUnlikely	100	0	0
Unlikely	50	50	0
Neutral	0	50	50
Likely	0	0	100
VeryLikely	33.3	33.4	33.3

Figure 2: Conditional probability node of Cooling Towers impact

These relationships have been used to identify scenarios that could occur because of events in the process of assessing the impact of location variables through four ranges for contingency between 0% and 20%, as shown in Figure 3. These contingency values have been presented based on the author's experience as proof of concept. Further research will be required to refine these contingency values.

Cooling towers	Technical labour sh...	0 to 5 percent	5 to 10 percent	10 to 15 percent	15 to 20 percent
Low	Low	100	0	0	0
Low	Medium	50	50	0	0
Low	High	0	0	100	0
Medium	Low	50	50	0	0
Medium	Medium	0	50	50	0
Medium	High	0	0	50	50
High	Low	0	50	50	0
High	Medium	0	0	50	50
High	High	0	0	0	100

Figure 3: Conditional probability node of Contingency for Mechanical

5.3 Performing calculations

The Bayesian network conditional probabilities were calculated using Netica software (Ni et al., 2011). This resulted in a functional and working network being developed to assess the impact of location variables. After calculations, the results of the conditional probabilities were established, as shown in Figure 4.

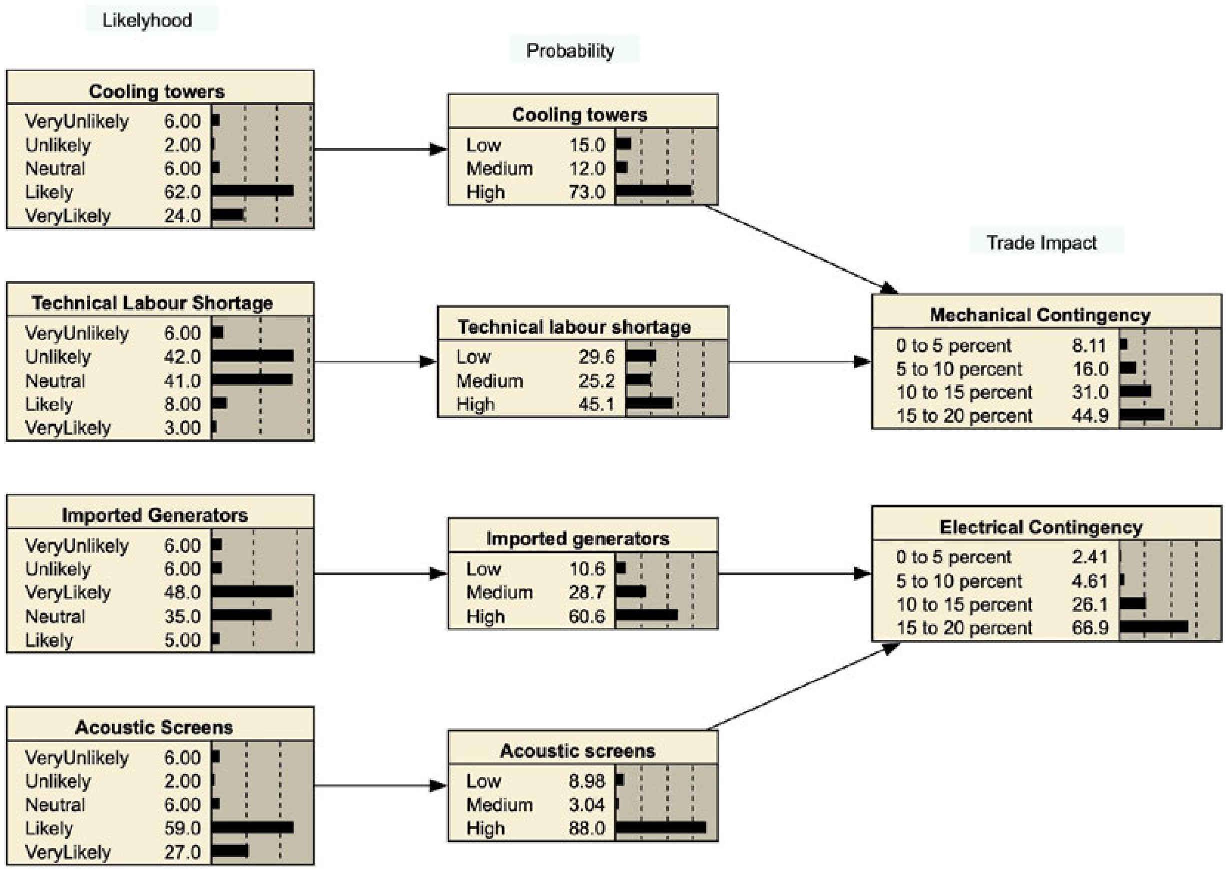

Figure 4: Bayesian network identifying trade Contingencies based on conditional probabilities.

5.4 Event scenario analysis

An example of the updated impact of Cooling towers is shown in Figure 5. This event has been modelled on the node ’Cooling towers’. A 100% likelihood of this event occurring has been assumed as ’Unlikely’ in this hypothetical scenario.

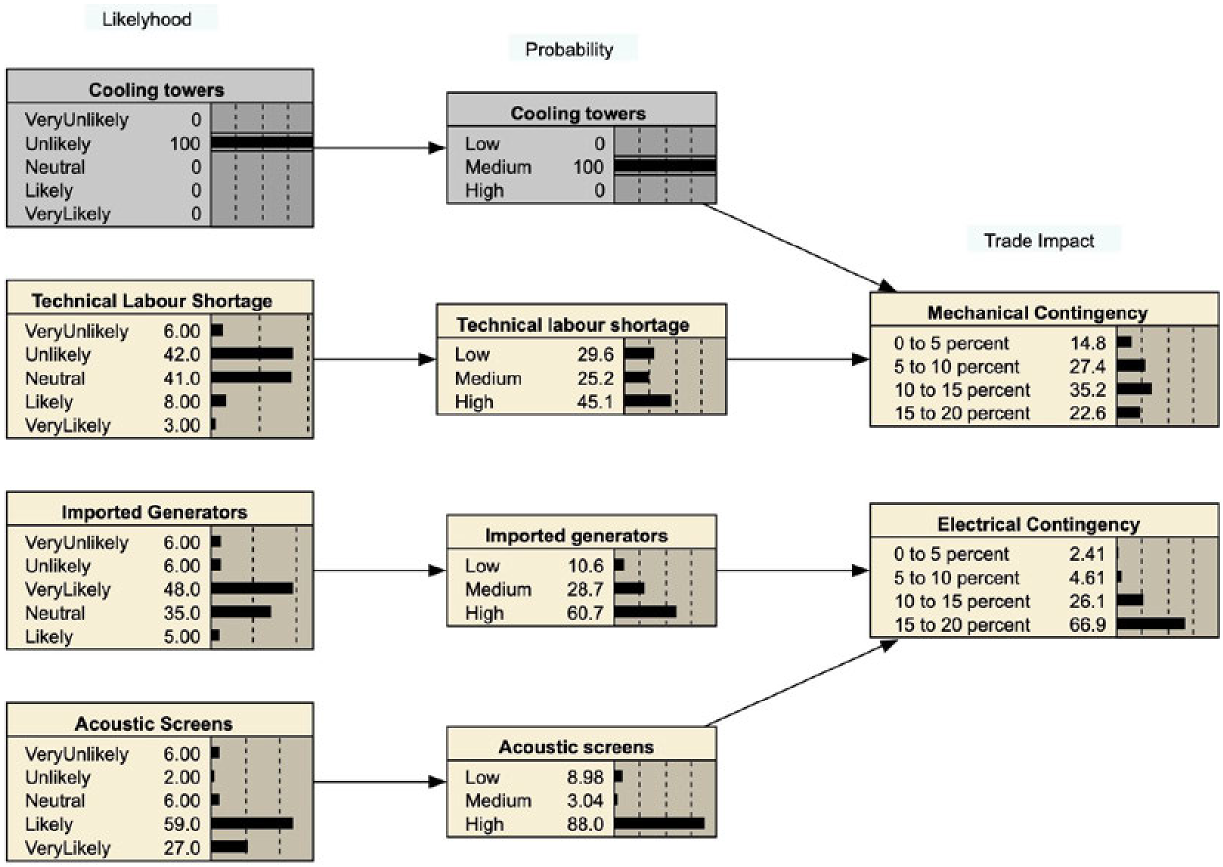

Figure 5: Bayesian network updated with new probabilities impacting Mechanical contingency.

In this scenario, we have also selected the node for a probability of an increase in cost to 'Medium.' Using this Bayesian network, this updated information has impacted the node for Mechanical Contingency, changing from 15%-20%, as identified in Figure 4, to 10%-15%, as shown in Figure 5. Therefore, in this example, the impact of location variables has, using the Bayesian theory, identified an improved risk and reduced contingency for the Mechanical Works.

6 CONCLUSION

Using a combination of the Delphi study, Likert scale, risk, and Bayesian theory to evaluate the impact of site location on capital expenditure for Hyperscale Data Centres has been demonstrated to be a feasible approach. The study findings indicate that it is possible to identify the likelihood of specific location variables impacting capital expenditure by conducting a Delphi study to obtain expert opinions and utilising a Likert scale to acquire subjective information about the probability and perceived risk of occurrence. These probabilities can be integrated into Bayesian analysis as prior knowledge, and as new information becomes available, they can be updated to calculate the posterior probability. The resulting percentage impact can then be applied to assess individual or multiple items and incorporated into the total capital expenditure, providing a method for determining the percentage impact, cost increase, or contingency. The findings of this study have significant implications for evaluating the impact of location variables for Hyperscale Data Centres, where variables can be identified and quantified as a percentage variance to capital expenditure. By utilising a Delphi study, the method can gather expert opinions, increasing the reliability and validity of the data obtained.

Furthermore, using a Likert scale allows for quantifying subjective information, which can be challenging to measure using other methods. Finally, by incorporating the probability and risk of occurrence, the Bayesian analysis provides a more accurate assessment of the impact of location variables on capital expenditure. The methodology described in this study can be applied to various industries, providing a comprehensive framework for determining the impact of various factors on capital expenditure and informing decision-making processes.

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UNIVERSITY ASSET DIGITALIZATION GUIDELINES: THE PILOT CASE OF POLITECNICO DI MILANO REAL ESTATE

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ABSTRACT: *This study describes a multi-year project aimed at digitizing the real estate assets of an Italian university, specifically the Politecnico di Milano. The objective is to enhance and streamline university asset management through the implementation of Building Information Modelling (BIM) methodology. BIM fosters a collaborative environment among stakeholders, facilitating the digitalization of asset management processes. The project focuses on modeling the university's assets in a BIM environment, for the creation of a repository of structured information that will streamline and optimize the processes related to the buildings' life cycle. This initiative aims to enhance real estate management services, optimize space utilization, and ultimately elevate user satisfaction within the university community. The project commenced with an in-depth analysis of the technical areas within the university responsible for design, construction, redevelopment, and overall real estate asset management. Each of these areas was evaluated for strengths, constraints, and critical points. Various approaches to BIM integration were explored to enhance digitalization processes. Based on these initial assessments, a comprehensive set of methodological and operational guidelines was formulated, encompassing modelling, management, and data-sharing aspects of digitalization. This paper provides an overview of the initial phases of the project, highlights its strengths, and identifies areas for improvement and testing in future project development. Emphasis is placed on standardizing information to ensure consistency throughout the asset's entire life cycle.*

KEYWORDS: *Building Information Modelling, Real estate management, University asset digitalization guidelines*

1. INTRODUCTION

The digital transition in the Architectural, Engineering, Construction, and Operation (AECO) industry has emerged as a priority in national policies, thereby garnering attention from administrative bodies. The AECO industry, however, remains relatively under-digitized, leading to diminished productivity. This is exacerbated by the fragmented processes within the industry, resulting in information loss throughout project lifecycles (Succar, 2010).

Frequently, the absence of accessible and up-to-date information underlies inadequate resource control in real estate asset management (Lauria et al., 2015; Meschini et al., 2022; Vivi et al., 2019). Incorporating operational strategies and digital tools like BIM into administrative procedures holds the potential to enhance data quality in decision-making processes, thereby fostering better-informed choices (Cacciaguerra et al., 2022; Derakhshan et al., 2019; Munir et al., 2019).

BIM's capability to construct digital building models incorporating information from various project stages provides valuable data for operations and maintenance across the building's lifecycle. Moreover, it transforms the relational dynamics among stakeholders involved in the construction process (Eastman, C., Teicholz, P., Sacks, R., Liston, 2008).

This research marks the initial phase of an extensive project undertaken by the Politecnico di Milano for asset digitalization, which started in 2021. The objective is to establish a BIM management system that enhances and streamlines real estate asset management through a digital transition process.

The project standardizes procedures and processes through the introduction of BIM methodology, aligning with the Polytechnic's endeavour to digitize building documents stipulated in the University Strategic Plan. This is achieved through proprietary guidelines and operational protocols. The development of these documents emanates from an analysis of the current organizational model's state, task and workflow assessments, and interdepartmental interactions. Consequently, the project identifies needs and revamps the organizational model to cultivate a collaborative environment among contributors to real estate development and management, integrating procedures.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Giuseppe Martino Di Giuda, Elisa Cacciaguerra, Francesco Paleari, Marco Schievano, Stefano Campi, Alessandro Tucci, *University Asset Digitalization Guidelines: The Pilot Case of Politecnico di Milano Real Estate,* pp. 407-418, DOI 10.36253/979-12-215-0289-3.40

This project holds replicable potential: Politecnico di Milano's digital transition process could serve as a pilot case for other university campuses, given the shared requirements and challenges of similar Italian institutions.

2. REFERENCE CONTEXT

2.1 Government BIM implementation and Guidelines

The role of governments in the successful implementation of BIM is crucial. Numerous studies have sought to evaluate implementation initiatives across various scales, investigating both limitations and drivers for adoption (Jiang et al., 2022). Challenges such as institutions unprepared for the market, high associated costs, and lengthy training periods have been identified as significant obstacles. Additionally, difficulties arise from a lack of clear standards and a structured approach to change management (Elmualim & Gilder, 2014). The adoption of BIM within construction processes remained sluggish until government institutions mandated its usage in public works projects. To achieve effective implementation, the legislative bodies must strategically plan and structure interventions to facilitate adoption. Many governments have championed initiatives aimed at advancing construction industry digitalization through BIM (Abdirad, 2017; Liu et al., 2015; Marocco et al., 2023).

Recognizing the increasingly acknowledged benefits of the BIM methodology, a growing number of nations have adopted comprehensive implementation strategies. In the United States, a leading figure in this domain, the General Services Administration (GSA) has mandated the utilization of BIM in all projects since 2007, with guidelines and standards developed by the National Institute of Building Science (NIBS) (National Insitute of Building Sciences US, 2023). The formulation of tailored guidelines, aligning with client needs, facilitates the generation of coherent information-rich models, essential for effective BIM implementation within organizations (Di Giuda et al., 2017). This underscores the importance of both public and private institutions establishing customized guidelines during the initial stages of transitioning to BIM, ensuring clear objectives and actions throughout all project phases.

Organizations equipped with well-defined guidelines can translate their requirements into precise information, thus ensuring the desired outcomes. Simultaneously, professionals and manufacturers can follow a structured work plan, fostering seamless collaboration and cooperation, and supported by standardized practices.

2.2 Regulatory background

The global and Italian legal and technical regulations governing BIM methodology draw upon references from both mandatory and voluntary standards. In the European context, Directive 2004/18/EC marked the initial directive, subsequently replaced by European Directive 2014/24/EU in 2014. Article 22 comma 4 of this directive emphasizes Member States' authority to "require the use of specific electronic tools, such as electronic simulation tools for building information or similar tools." This directive compels member states to incentivize, specify, or mandate digital tool adoption through dedicated legislative measures. In Italian law, this directive was adopted by Delegated Law n. 11 of January 28th, 2016, and subsequently confirmed by D.Lgs 50/2016, followed by its implementing decree (DM 560/2017), and the recent D.lgs 36/2023, which reinforces the significance of digitalization across the entire procurement lifecycle. This decree outlines the incremental, mandatory introduction of BIM in public procurement. Organizations are obligated to establish a comprehensive plan for staff training, hardware and software acquisition and maintenance for digital decision-making and information management processes. The decree underscores the importance of an organizational framework that articulates the control and management of information and related aspects. DM 312/2021 incorporates elements from the preceding decree, explicitly stipulating that models should be accompanied by decision-support workflows. Furthermore, this decree references the use of technical specifications in accordance with voluntary European technical standards (EN or EN ISO), international technical standards (ISO), and national technical standards (UNI). Notably, in the construction industry, relevant standards encompass the ISO 19650 Series on BIM-based information management, the UNI 11337 Series on digital construction information process management, the ISO 21500 Series on project, program, and portfolio management, the 55000 Series on asset management, and the ISO 9000 Series on quality management.

3. DIGITALIZATION ROADMAP METHODOLOGY

One of the principal challenges of a digital transition process is related to the need to implement a new working logic within practices that are not always regulated but are well-rooted and difficult to change (Ahmed et al., 2017; Barbosa et al., 2017) Moreover, the necessity to maintain information at the core of the construction process throughout its different phases is a key aspect of BIM methodology and necessitates the practical application of concepts such as information sharing and standardization. This often becomes critical as the individuals responsible for managing information during the various stages of the building's life cycle are diverse and handle an array of disparate or non-uniform information.

This research introduces the initial stages of the digital transition process within a public university, which began in 2021 and anticipated to be completed over approximately six years. It is segmented into three strategic work phases. The project's long-term objective is to execute the digital transition process for the digitalization of the university's real estate and its management procedures through BIM (Fig.1). The proposed methodology can be readily replicated for other university real estate assets.

The project addresses the need to integrate the new digital work methodology into an organization with established processes while striving to strike a balance between coexisting established practices and implementation of new ones. To achieve this, a framework was established across three consecutive and interconnected phases, progressively integrating novel methods. Emphasis was placed on optimizing work processes and resolving critical issues primarily stemming from information loss during the transition from building design to management phases. Maintaining the structuring and management of information vital for the building management phase remained the focal point of the project.

The first phase represents a strategic stage, during which strategic macro-objectives of the digitalization project were defined. The research context was examined, organizational processes were analyzed, and project-specific objectives were formulated, aligned with regulations for optimization purposes. This phase culminates in the creation of the Methodological Guideline, a strategic document that elucidates project objectives and the application context, outlines the document structure comprising the Guideline, and delineates the roles of involved stakeholders.

The following phase, the application phase, focuses on delineating the information content of digital models through the development of operational documents. These documents outline modeling specifications, element hierarchies, information granularity, and asset attributes. The phase concludes with the initial implementation of case studies to validate guideline content.

The ongoing third phase involves the practical integration of BIM into facility management, enabling comprehensive utilization. This phase necessitates comprehensive staff training to ensure the adoption of guidelines and their gradual integration into strategic projects, ultimately leading to their universal application.

The described workflow, reflected in the hierarchical structure of the Guideline's documents, is characterized by three levels:

- Methodological Guideline: The primary document defining the foundational principles underpinning the application of BIM methodology within the university's processes.
- Operational Documents: These executive documents address specific concerns.
- Project Operational Documents: templates for specialized documents mandated by regulations in contracts.

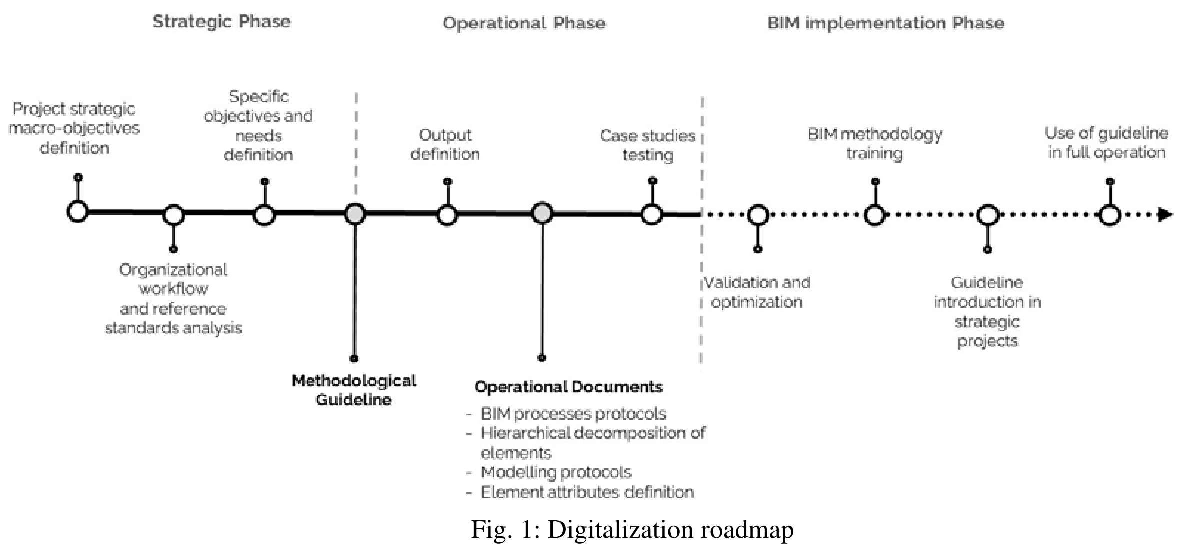

Fig. 1: Digitalization roadmap

4. POLYTHECNIC OF MILAN CASE STUDY

The Polytechnic's real estate holdings are spread across six campuses situated in different cities, comprising a total of 117 buildings and covering an extensive area of 467,000 square meters. The university community comprises approximately 53,264 individuals who engage with and utilize these facilities in various capacities. These include students, researchers (including research fellows and PhD students), professors and technical and administrative staff (Fig. 2).

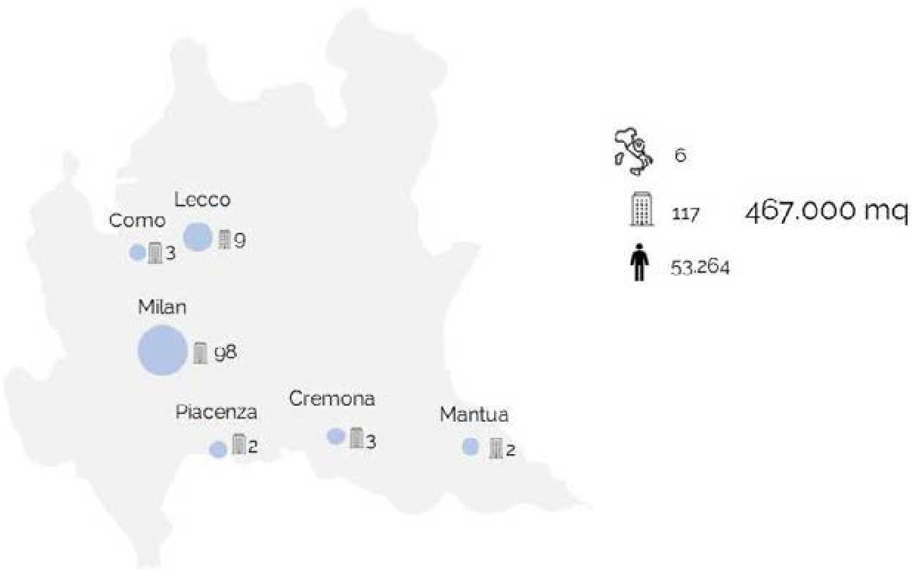

Fig. 2: Consistency of the real estate assets of the Politecnico di Milano

The Politecnico di Milano is a large, complex organization and its management is quite challenging. To address this complexity, the institution has undertaken the development of the BIM Management System Standards. These standards have been devised while considering the regulations pertaining to quality, asset, and project management, as well as information management. While the adoption of these regulations remains partial within the technical domains and their associated activities, the overarching goal is to achieve comprehensive integration into all operational processes. Such integration is anticipated to yield intricate synergies, fostering streamlined operations while concurrently minimizing both effort and expenses.

The following sections provide an overview of the stages completed to date in this ongoing process.

4.1 Strategic and organizational Phase

4.1.1 Organization chart and existing processes analysis

Achieving a successful digital transition process requires integrating change with existing processes. Therefore, the initial phase of the process was dedicated to comprehending the organization and its operational logic, achieved through an in-depth examination of the departments involved in the university's building processes.

At the organizational level, a dedicated BIM Task Force was established at the central university level to oversee the project. This Task Force, comprised of technical and research personnel, was specifically constituted for this purpose.

By examining the organizational structure, the primary departments engaged across all stages of the building process were identified (Fig.3):

- Technical Building Area: This office assumes responsibility for the strategic planning and coordination of real estate development, encompassing activities such as extraordinary maintenance, restoration, rehabilitation, building renovations, and new construction.

- Infrastructure and Services Management Area: This office tasked with maintaining university spaces, ensuring their livability, security, cleanliness, and the provision of services and resources essential for administrative operations.
- ICT Services Area: This office manages the provisioning and administration of ICT services, facilitating the cohesive management of information in support of governance, administration, and all stakeholders. Its primary role within the process is to facilitate information management.

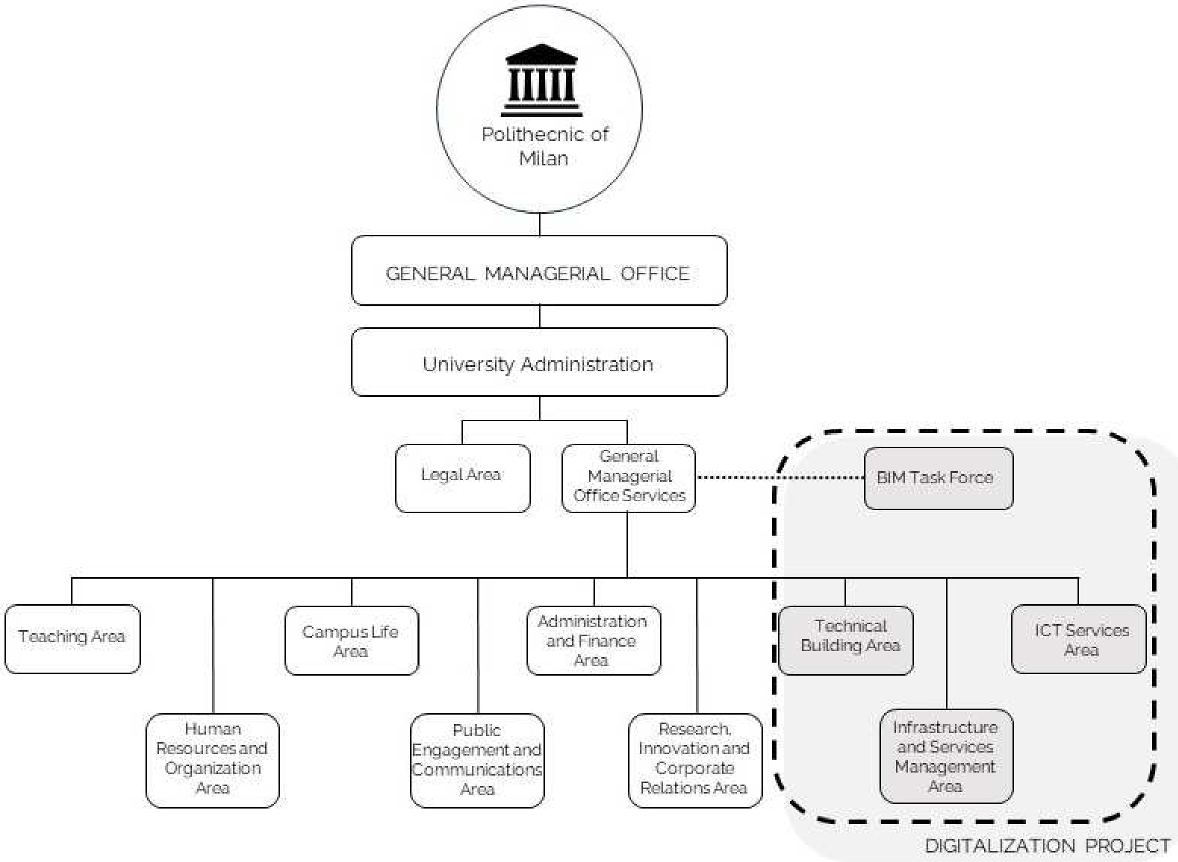

Fig. 3: Examination of the University Organizational Structure and Identification of Involved Departments

The workflows of these offices were studied through the analysis of the documentation provided and a survey campaign, with the aim of learning about the procedures and interactions between internal and external parties and assessing possible problems.

This phase of the offices analysis occurred in two cycles:

- The first cycle involved conducting standardized interviews across all offices to identify characteristics, responsibilities, tasks, and structural facets. It further sought to analyse the means of communication, document exchange, and interactions among individuals, both within offices and across different departments and external entities.
- The second cycle encompassed tailored interviews for each office, delving into specific inquiries pertaining to the adoption of information modeling, particularly during the design and management phases.

The main critical issues highlighted by this analysis were:

- Difficulties in collaboration between offices.
- Inadequate management of the document exchange from construction to building management phases.
- Unclear delineation of roles and responsibilities throughout distinct stages of the construction process.
- Absence of standardized storage systems.

- Inaccurate or incomplete building information.
- Lack of uniform and shared coding across offices of spatial and technological-functional elements.
- Absence of protocols and technical specifications for the transition from the design phase to the management phase.
- Lack of a definitive list detailing elements to be maintained and their associated attributes.

All existing processes were then mapped and diagrammed through Business Process Model and Notation (BPMN), an internationally recognized open standard that provides a graphical notation for specifying an organization's processes. This graphical notation system has gained prominence within the AECO industry due to its capacity to simplify comprehension between individuals with diverse backgrounds enhance interoperability. The schematic representation of processes promotes clearer apprehension of tasks, roles, and information exchanges, and consequently, information requirements (ISO 19560) are defined. In that way, processes are translated into a computing language, making possible future automation (Fleischmann et al., 2012; Meschini et al., 2023)

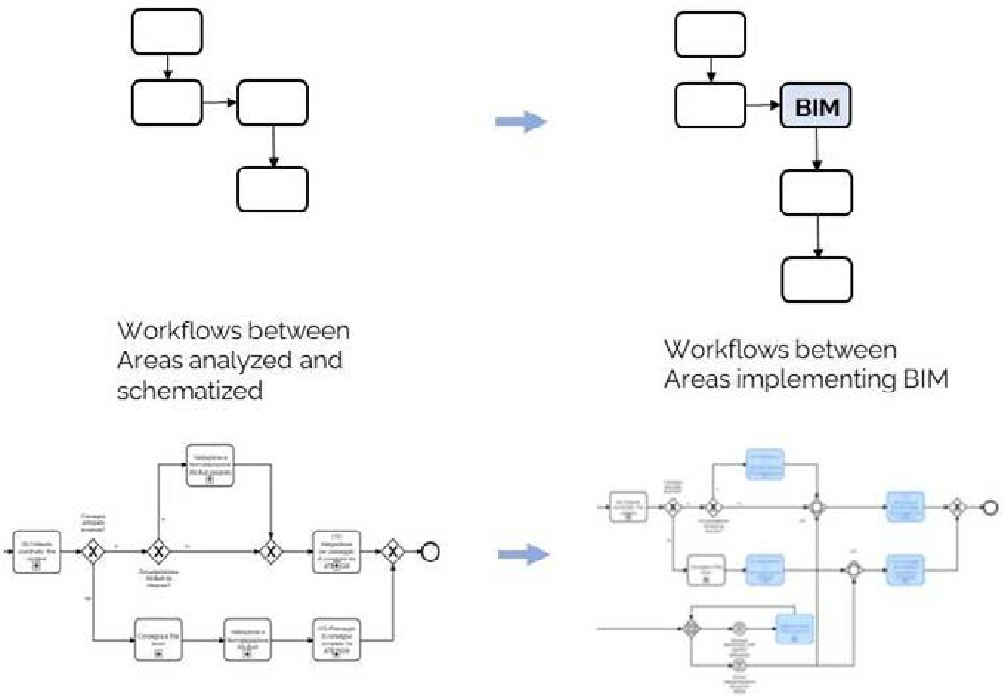

Fig. 4: Exemplification of a BPMN extrapolation illustrating an analyzed process and its redesign proposal through BIM.

Processes have been classified into three categories:

- Main processes: These encompass workflows that involve activities spanning multiple departments. They relate to tasks such as designing and constructing new buildings, revitalizing existing structures, and initiating property management.

  These can be represented in:

  - Process models: sequence or flow of activities with the goal of accomplish a task;
  - Collaboration models: a set of processes that work together for a purpose and are individually referred to as actors involved in exchanging information.

  Main processes may contain sub-processes and recursive sub-processes, which may be process or collaboration models:
- Sub-processes: These represent processes identified within main processes.
- Recursive sub-processes: These further delineate processes within main processes, outlining a series of activities conducted between departments. These sub-processes can be invoked within various higher-order processes.

After sistematically analyzing existing processes, a proposal to reimagine these processes using a BIM-based approach was formalized. This proposal underwent subsequent rounds of review, revisions, and validation by the offices that had been previously investigated (Fig.4).

Furthermore, an updated organizational chart was devised, introducing new roles within each department. These additions catered to the responsibilities of individuals resulting from the integration of BIM into processes, as mandated by technical regulations.

4.1.2 Defining the specific goals and Organizational needs

The specific objectives of the project were established by deriving insights from the strategic objectives defined within the transition process framework. This process was further informed by an analysis of the structure and evidence of critical issues uncovered during the process study.

This was supported by the BPMN flows study, which examined the path and importance of each piece of information throughout the building process, from the design phase (Technical Building Area) to the management phase (Infrastructure and Services Management Area).

The needs of the new building asset management system were identified with respect to the needs of each of the previously identified offices, with the aim to solve the highlighted critical issues. In particular, the new building asset management system must ensure collaboration among the subjects by optimizing building management through coordination among various project disciplines. The need to collect information consistently despite different data collection occasions must be considered to ensure reliable and up-to-date information in a single BIM repository of as-built BIM models (Fig.5).

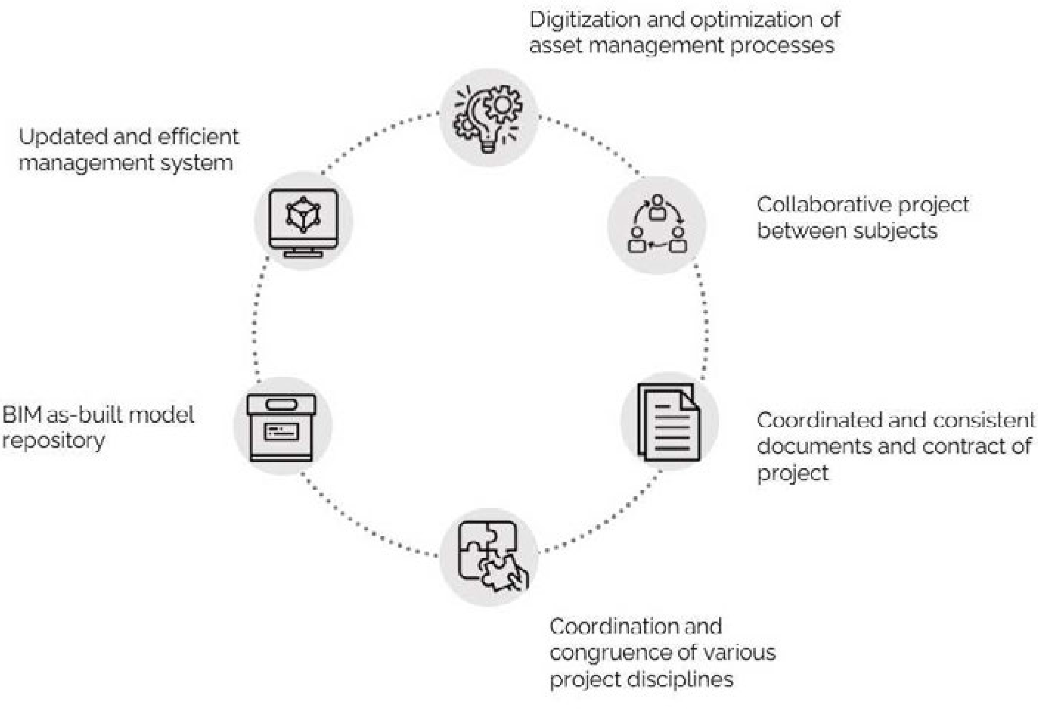

Fig.5 Goals of the New Building Management System

This new system is characterized by its focus on shaping a dataset of information tailored to enhance real estate management. Through this strategic emphasis, the project aims to forge a comprehensive and coherent solution to the challenges identified within the organization's building processes.

4.2 Operational Phase

4.2.1 Define the information requirement

Defining information content is essential for proper asset management through BIM methodology. Within the Politecnico di Milano Guideline was based on the guidance provided by the UNI EN ISO 19650 and UNI 11337 series of standards.

Central to this initiative is the concept that information should be produced and retained with a distinct purpose. The process of defining information requirement revolves around outlining the specifics of the information to be generated and preserved, all with the overarching goal of ensuring that whatever the stakeholder's role, the subsequent objective is achieved seamlessly. Organizations able to govern the management of information during the processes allow the progress of both internally and externally coordinated operations to be made fast and uninterrupted, obtaining only the products they need, avoiding unhelpful material, and guaranteeing the quality of the information obtained.

Therefore, it is essential to establish a structure capable of managing requirements to ensure the effectiveness of data production, collection, and exchange throughout the process. Client awareness regarding the value of information content also clarifies client requirements for various aspects, such as production and sharing methods, delivery times, and formats. Furthermore, this awareness supports the development of verification and control methods.

The approach to defining information content for the Polytechnic is based on three concepts:

- Information needs level: detail with respect to quality, quantity, and granularity of data to be adopted to define information related to a purpose.
  Information that makes explicit the level of information need is divided into:
  - Geometric information
  - Alphanumeric information
  - Documentary information
- Granularity: degree of subdivision and specification of information management levels;
- Data aggregation strategies: ways in which data should be aggregated or disaggregated.

The process of defining information requirements for the real estate assets of the Politecnico di Milano was motivated by the need to address critical issues identified during the study of information flow throughout the processes. Specifically, the investigation focused on the issue of data collection's relevance to the maintenance phase under different circumstances.

One of the issues found was the mismatch of elements from the design phase to the maintenance phase. This problem was leading to a mismatch between the data entered into the archives during the design phase and those entered during the maintenance phase, resulting in the need to re-search the information with a consequent loss of time. This lack of correspondence, combined with the absence of an unambiguous listing of assets to be maintained and the sharing of related management information requirements, led to the inability to record the related operations performed on the items, resulting in the impossibility of timely control their maintenance status and standardization of contracts.

The subsequent focus of the endeavor was on establishing a unified and shared asset list for the As-Built and maintenance phases. To achieve this objective, the technological-functional elements that were previously employed by the Technical Building Area (a Project Breakdown Structure that segments the project into its technological elements used in the design phase) were examinated. Subsequently, we formulated an inventory of homogeneous objects that amalgamate various technical elements related to maintenance contracts. This endeavor culminated in the creation of a new asset list that seamlessly binds these components together (Fig. 6).

Through the establishment of this unified asset listing, bridging the technical aspects of the design phase with maintenance-oriented elements, the attributes requisite for each identified element during both design and maintenance phases were effectively defined. This meticulous approach ensures the determination of the minimum essential information required for each phase.

The level of information detail required will vary during different phases of the building's life and will be managed to streamline the recording of essential data, optimizing the time dedicated to information census and modeling. At the same time, the quality of the information entered into the system must be excellent, with the goal that it will always be completely reliable.

To ensure cohensiveness across all information derived from models, at whatever stage of the asset life cycle these were produced, the operational document "Modeling Protocols" was formalized. This is a document that makes explicit the rules and guidance necessary for the development of information models within the University's BIM Management System. The document aims to ensure a defined and shared BIM model structure.

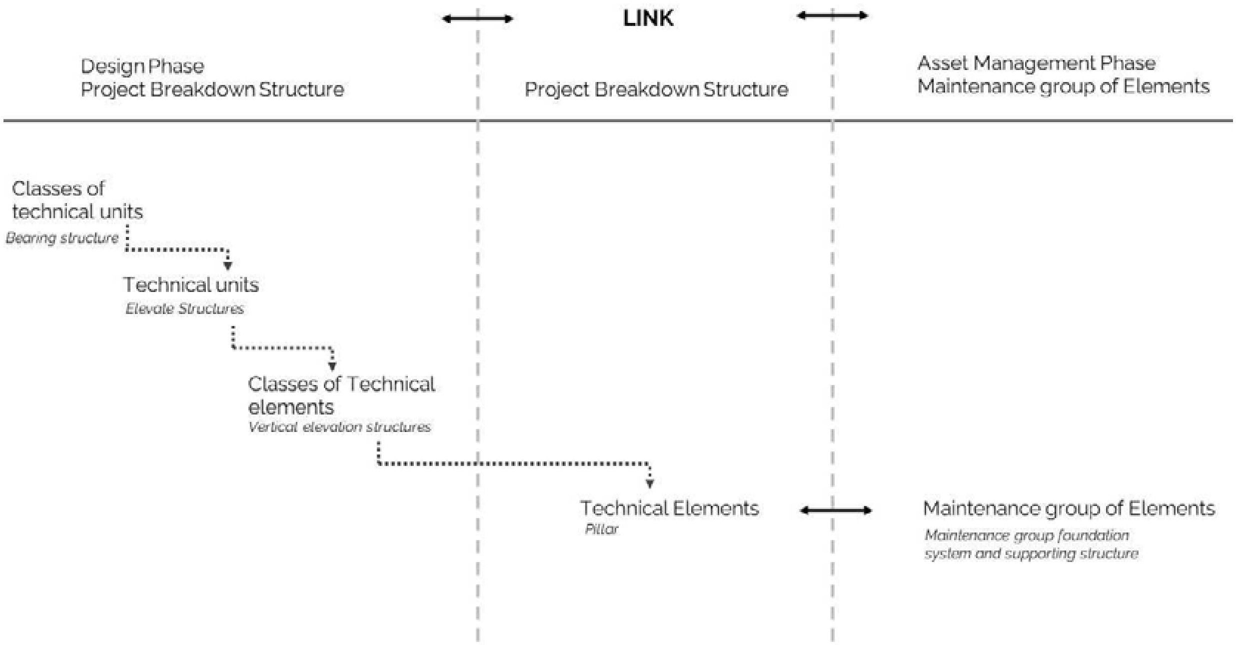

Fig. 6 Relationship between hierarchies of elements in the design and in the maintenance phases

The requirements underpinning the regulation of BIM Modeling in the document, which is based on the relevant legislation, are (i) the definition of a clear and shared structure, (ii) the need for continuity between pre-existing processes in terms of models and software, and (iii) streamlined models that can be used and reworked efficiently while ensuring the exchange of information.

The protocols are structured with consideration of three information modeling scenarios that the Organization may face:

- new construction interventions.
- representation of the existing.
- existing redevelopment interventions.

The paper explicitly outlines the technical characteristics models must possess to ensure consistency within the management system. A particularly important aspect of ensuring consistency between model elements is the mapping process, which relates elements to: (i) the Product Breakdown Structure of the assets previously illustrated, (ii) the categories of the modeling software chosen by the university, (iii) and the related entities for exporting the models in open format IFC (Industries Foundation Classes) ensuring interoperability (Laakso & Kiviniemi, 2012) (Fig. 7).

Throughout the transition project, we identified software to be used for information management based on various purposes. Rearding modeling, information collection, and management in the later phase, a comparative evaluation of FM and CDE software was conduced to determine the most suitable ones at the technical level according to the University’s requirements.

To validate the correctness of protocols and decisions in the operational documents, two pilot buildings were modeled following the guidelines. Pilot cases were selected to test an already existing building and a new construction project, ensuring that each.

Product Breakdown Structure Asset	Proprietary BIM authoring software Category	Non-proprietary software entity
Pillar	Structural Columns	IfcColumn
Stair	Stair	IfcStair
Window	Window	IfcWindow
Boiler	Mechanical Equipment	IfcBoiler

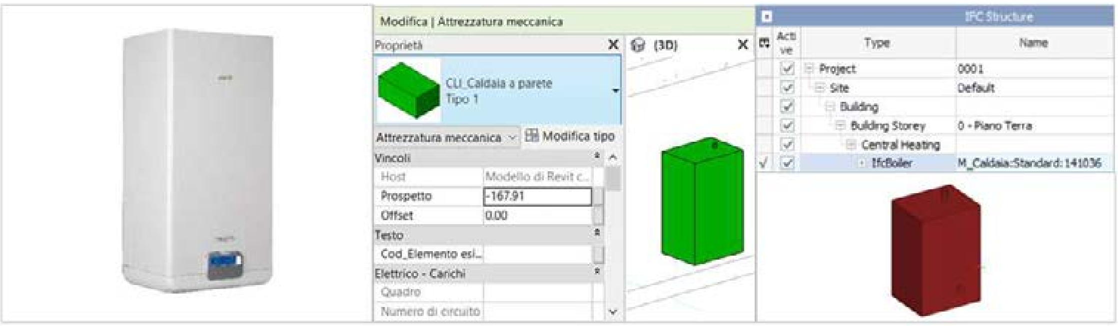

Fig. 7 Example of boiler element mapping

5. FIRST RESULTS DISCUSSION AND FURTHER DEVELOPMENT

To date, the digitalization project of the Politecnico di Milano organization is an ongoing process expected to be completed by 2026. The first two phases of the project have concluded successfully with the approval of the Methodological Guideline and Operational Documents, detailing specific features of information modeling. These documents were validated through the modeling of two case studies to verify the accuracy of the decisions made.

The University Governance intends to base new procurements addressing the university's space needs on these approved Guideline documents. This approach ensures that new construction adheres to defined rules, gradually populating the university's BIM repository with consistent information. The ability of external parties to use the Guideline will enable the research team to validate comprehension and correctness in data reception, addressing and resolving any issues through updated document versions. Therefore, establishing protocols for internal data verification is essential.

The subsequent phase of the digital transition project involves the actual implementation of the BIM methodology within the organization. This phase commences with comprehensive training for the offices on the use of the Proprietary BIM Guidelines and compliance with the new standardized procedures. This training ensures their assimilation and prevents the distortion of client requirements in terms of information content over time, which could render the entire data processing process ineffective.

6. CONCLUSIONS

This work explored the implementation of a digital transition process for the property management of a large university. The application research was structured in three progressive phases, aiming to optimize the management of the information flow through process implementation, resulting in improved management of the entire building process while structuring information essential for the real estate management phase.

The specific focus was on defining a consistent information set derived in part from existing processes. The implementation addressed critical issues related to the loss of useful information during the transition from the design phase to the management phase. The definition and subsequent verification of information requirements by the organization are essential for properly aggregating and disaggregating information as needed.

For this type of process to succeed, the organization must possess proprietary Guidelines aligned with its processes and requirements while internally training its staff to recognize the importance of maintaining consistent information content.

7. ACKNOWLEDGEMENT

The authors express their gratitude to the Politecnico di Milano offices involved in the process for their valuable contribution and collaboration.

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BIM-GIS AND BI INTEGRATION FOR FACILITY AND OCCUPANCY MANAGEMENT OF UNIVERSITY ASSETS: THE UNITO PILOT CASE

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ABSTRACT: *The integration of Building Information Modelling (BIM) and Geographic Information System (GIS) with Business Intelligence (BI) is promising for managing vast and diffused assets. It enables valuable insights into asset performance and resource uses, supporting savings, improved efficiency, and sustainability. The research proposes a web-based Asset Management System application (AMS-app) via BIM-GIS-BI integration, providing an updated digital representation of university assets by combining spatial, performance, and operation data with related analytics. The AMS-app was developed in the context of the University of Turin's strategic plan as a pilot case to improve asset management procedures through a data-driven approach. Indeed, campuses are complex assets managed by multiple actors through still document-based and fragmented databases, often leading to ineffective and untimely decision-making processes. The AMS-app represents a valuable decision support system for facility managers aimed at asset monitoring and user experience improving through better and more sustainable decisions concerning space, occupancy, and indoor environmental quality (IEQ). To demonstrate the effectiveness of the BIM-GIS-BI integration through the AMS-app, several case studies were implemented with the following objectives: (i) the digitalization of university building data, (ii) the optimization of courses timetables according to space availability, (iii) the optimal workstations management, and (iv) the analysis, monitoring and optimizing of IEQ and comfort via IoT networks. The paper illustrates the advantages and applicability of the developed methodology through the case studies, and further developments in university asset management.*

KEYWORDS: *Asset Management System, BIM-GIS integration, Business Intelligence, Information management*

1. BACKGROUND AND MOTIVATION

University assets, especially Italian ones, are characterized by strong management complexity due to their diffused buildings, often built in different eras with various construction technologies and high heterogeneity. The management is often based on fragmented, incomplete, and hardly accessible databases, preventing the correct definition and optimization of usage patterns, as well as the normalization of management processes (Qian and Papadonikolaki, 2020). This results in inefficiencies in services and maintenance activities, leading to wasted resources and inefficient decisions concerning the expected performance, user comfort, and economic and environmental sustainability. Thus, university assets represent a crucial opportunity to propose a solution to the information gaps currently found in managing large assets. There is an increasing need for the adoption of information management strategies aimed at shifting from highly document-based and fragmented approaches to digital and collaborative ones (Chen et al., 2015). Digital tools and effective information management strategies enable data integration, ensuring the availability of accurate information with various granularity levels, at the right time, in the required formats, and throughout the asset lifecycle. Despite its application in asset management is still rare (Moretti et al., 2021), BIM-GIS integration provides high potential (Liu et al., 2017; Beck et al., 2020), especially in borrowing the Smart City concept at the Campus scale, improving the management of such complex assets for a better user experience and optimal resource utilization (Lu et al., 2020; Ward et al., 2021; Wang et al., 2019). BIM enables the development of highly detailed building information models, while GIS allows their management and analysis through a global spatial reference system (Zhu et al., 2021). BIM-GIS integration combined with BI tools can be exploited to optimize the management of large assets and to foster the development of AMS tools as concrete decision support systems (Pärn et al., 2017). The further integration of IoT and digital devices can facilitate data collecting, providing a better maintenance and asset management through the monitoring and analysis of real-time data about asset performance and condition, enabling timely interventions (Wong et al., 2018).

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Giuseppe Martino Di Giuda, Daniele Accardo, Paola Gasbarri, Silvia Meschini, Lavinia Chiara Tagliabue, Laura Scomparin, *BIM-GIS and BI Integration for Facility and Occupancy Management of University Assets: The UNITO Pilot Case*, pp. 419-430,
DOI 10.36253/979-12-215-0289-3.41

The research project exploits BIM-GIS integration with BI tools to develop an interactive, web-based 3D map (AMS-app) for the management of large and diffused university assets. The main objective consists in facilitating information management and decision-making processes by improving information accessibility and sharing among stakeholders, and normalize management processes. The paper illustrates the replicable methodology developed to define and implement the AMS-app within the management system of the University of Turin (i.e. UniTO), an emblematic case for testing and demonstrating the potential offered by such a decision support system. Then it describes how data are collected from various siloed databases and integrated, providing an easily accessible and implementable knowledge base. Indeed, the AMS-app collects all the data currently handled separately by different administrative offices, providing a still independent but collaborative management system. Thus, the asset can be managed at the system level, rather than at the level of individual isolated buildings. The potential that such an AMS-app can provide to asset and facility managers of large university assets is described through the illustration of several case studies implemented so far, selected based on the management needs encountered within UniTO. Finally, the results are discussed, and the potential future developments and implementations are reported. Further objectives concern the development of information modelling protocols and guidelines to facilitate the adoption and transition to such a digitalized and shared management approach. In this way, the data can be modeled and structured ensuring the availability of accurate information at the right time, in the required format ,throughout the asset lifecycle, and the method can be easily replicated.

2. METHODOLOGY

The main steps of the methodology adopted to develop and implement the AMS-app in the university organizational structure are illustrated in the following paragraphs.

2.1.1 Main objectives and needs definition

The first step concerns the definition of the main objectives and needs that the organization intends to handle via the AMS-app. The organizational structure was analyzed to understand the management issues faced by UniTO and to define the relevant case studies to be implemented and tested through the AMS-app. Consequently, meetings and interviews with the managers of the technical areas in charge of the university asset management, its maintenance, information systems management, as well as teaching and educational services were conducted.

2.1.2 Current database structure and dataflow management strategies investigation

An investigation of the procedure currently adopted by the university to manage the information flow has been conducted to identify which information and data are handled by the different technical areas, as well as the methodology used to produce, store, and exchange them. One of the main aims of the analysis concerned the identification of the tools and formats currently exploited by the areas so that the AMS-app could be developed without disruptively changing current workflows, facilitating its adoption.

2.1.3 Organization information exchange and information requirements formalization

Once identified the organization's current database structure and dataflow management strategies, the analysis and formalization of the information exchange among the technical areas have been performed. The main aim was to ensure the easy integration of modifications occurring over time, providing a constantly updated digital representation of the building asset. The information exchanges were formalized to ensure that the technical areas can continue to rely on current tools and procedures with minor changes in data production and management. Then, the Information Requirements (IRs) have been defined to foster communication and support the creation of a coherent database to feed the AMS-app. Table 1 provides an example of an exchange information requirement schedule.

Table 1: Example of an exchange information requirement in the standardized form for data collection.

Field	Data source	Note	Type
Building code	OpenSIPI, Technical Areas: EDISOS, SILOM, SIPE, Asset Management	Building coding (Settlement_Building: e.g. 029_B)	Text
Building name	OpenSIPI, Technical Areas: EDISOS, SILOM, SIPE, Asset Management	Free field	Text
Main address	OpenSIPI, Technical Areas: EDISOS,	Free field	Text

	SILOM, SIPE, Asset Management		
Municipality	OpenSIPI, Technical Areas: EDISOS, SILOM, SIPE, Asset Management	Extended name, es. Turin	Text
Main use	OpenSIPI, Technical Areas: EDISOS, SILOM, SIPE, Asset Management	Free field	Text
Building Type	OpenSIPI, Technical Areas: EDISOS, SILOM, SIPE, Asset Management	Bound field: Building, Portion of Building, Agglomeration of Buildings, No Type, ND	Text
Status	OpenSIPI, Technical Areas: EDISOS, SILOM, SIPE, Asset Management	Restricted field: Decommissioned, In use, Under construction, No Status, NDo	Text

Furthermore, a possible change in the university's organizational structure was investigated for better supporting the AMS-app adoption.

2.1.4 AMS-app development: approaches, technologies, and tools selection

As stated before, the scientific literature has widely discussed how BIM and GIS integration can bring significant benefits in the field of asset management. BIM enables an overview of a single building and GIS allows the contextualization of each building, enabling analysis at a territorial level. Thus, the two resources optimally lend themselves to the university campus management, which, given its complex infrastructure, the amount of heterogeneous data, and spaces spread over a vast territory, needs systems that can facilitate the management, use, and maintenance of their assets at different levels. The proposed system integrates these resources providing the necessary tools for understanding, visualizing, and analyzing information related to the university building stock, its services, and infrastructure, thanks also to the support of BI tools. Data are core to the system, populating it and being the key to the different components' connections. The platform integrates data of various nature and from multiple sources: geographic data, geometric and functional data, as well as data concerning IEQ derived from sensors (Table 2).

Table 2: Data sources, information and types.

Source	Information	Type
Piedmont Territorial Geoportal	Building location, heights, geometries, restrictions	Text, numbers, coordinates, shape files. Static data.
OpenSIPI	Name, encoding, address, floor numbers, state of use, geometries, area, department assignment	Text, numbers, drawing. Static data.
Department offices	Courses schedule, personnel employed information, buildings construction site	Mainly text. Sheet-form organization. Dynamic data (on long term)
University website	Timetables, organizational units, building property state and expenses	Mainly text. Sheet-form organization. Dynamic data (on long term)
IAQ Platform	Environmental sensors measurement (CO2, humidity, temperature, VOC, PM2.5, etc.)	Numbers. Dynamic data (on brief term)

The different datasets are then collected from various sources, processed, and stored in a cloud repository so that data can be queried by any operator without duplicates, errors, or information loss. Aiming at the optimal integration between the different data, information sheets have been prepared and provided to the technical areas, asking for their fulfillment. Nonetheless, their compilation is not always possible such as in the case of geometric data derived from drawings or models, or geographical data from cartographic services such as the Geoportal of the Piedmont Region. In these cases, the sheets have been compiled manually by the authors.

Once the needed data have been collected, they are interlinked thanks to the semantic association of encoded names. An encoding system was defined for each city, building, and space, which is part of the university asset, starting from the one currently used by the university's administration to promote a smooth integration process. The encoding system was also key for data association in GIS. The entire campus buildings were identified, geolocated, and associated with their encoded names. The map was developed in a 3D view, aiming at offering a better perception of urban space, asset consistency, and distribution. Thanks to the geolocation of the encoded buildings through a 3D environment, and to the association with functional data, various analyses were developed at the territorial level, providing the depth knowledge of the university asset with information on its use and consistency, useful to support decision-making processes.

QGIS was selected for the shape files creation and first population, while Mapbox was exploited for the 3D map development and visualization. It was chosen for its easy integration with Microsoft Power BI, thanks to the opportunity to generate a customized web map based on the created shape files, shareable through URL and carrier of selected information. In addition to the GIS representation of the university asset, BIM was exploited for the analysis and visualization of each single building at different levels. The modeling phase succeeded in exploiting the Autodesk Revit Software for geometrical construction and the Visual Programming Language Application Dynamo for information population. The BIM modeling and the Dynamo nodes were developed with the aim of generating a replicable workflow, adaptable at each building of the asset. So, each BIM model presents three different levels of consistency: the building volume, the building levels, and the building spaces, modeled as mass, floors and rooms, respectively. Each element is firstly associated with the corresponding code, then the encoded name and the Revit Element ID are exported for each geometry modeled. The encoded name association ensures the association between the different datasets, but the connection between the BIM geometries and the information occurs via the Revit Element ID association. It is needed for various reasons, for example, some rooms may temporarily present the same encoded name during a space renovation, or their geometry can change throughout the building lifecycle, as well as their name. Despite the mutability of information such as the name, the Revit Element ID remains unchanged over time.

The BIM model is then associated with information related to the standard use of the building and its characteristics. During parameters' creation, a parameters comparator enables to individuate the shared parameter between masses floors and rooms, avoiding repetition that could lead to association errors or can compromise the final model quality. Both the Revit parameters and the associated values are extrapolated by the same dataset, stored in the cloud repository, and in the future, each building of the university asset will have its own datasets for better management. At this stage, the association of the most dynamic information, such as the real-time collected data, has been avoided. In this way, the model can represent the basis for multiple analyses related not only to environmental quality but also to space occupancy or educational and working spaces management. This choice provided also lighter models, with smaller file sizes and greater smoothness. Finally, with the aim of facilitating BIM and Microsoft Power BI integration, the BIM model was exported with Proving Ground Tracer. This software allows the exportation of both 2D and 3D geometries with related information, all preserved in an SQL database generated by the software itself. At the end of the process, the BIM is then ready to be imported and visualized in Microsoft Power BI. It demonstrated great capacity in data analysis and visualization, allowing information sharing between different stakeholders through analytic dashboards which can involve data, BIM models, and GIS maps. So, it represents the preferential software for web-app structure development.

2.1.5 Data visualization, analytics, and dashboard structure definition

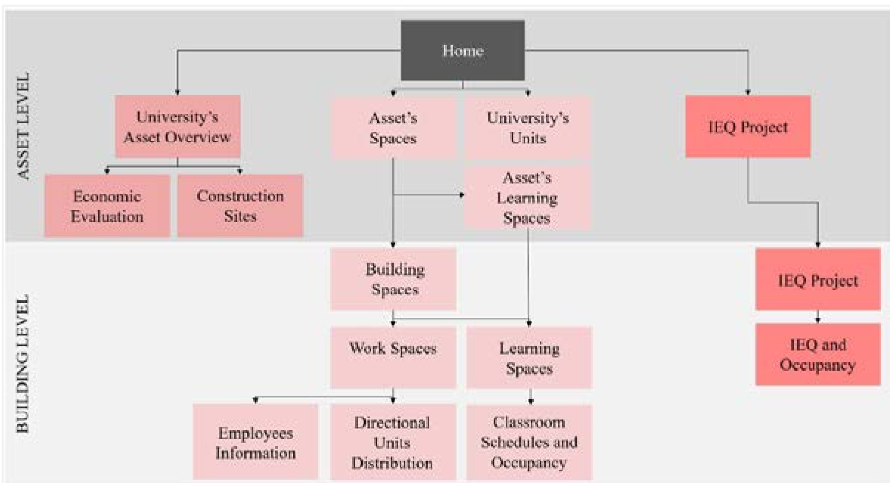

Fig. 1: UniTO's asset management system platform based on BIM-GIS-PBI integration

Power BI was chosen not only for data analysis and visualization but also as the software to generate the AMS-app main structure. The dashboards created are directly connected to datasets stored in the cloud repository and can be integrated with BIM and GIS maps. Thanks to these connections, based on the relationship of the encoded names, it's possible to associate the resources, the data previously excluded, such as the dynamic data related to real-time environmental quality measurement, the course timetables, the occupancy rates, etc. The platform is structured so that the dashboards are gathered in thematic reports (asset consistency, economic evaluation, construction sites, IEQ, spaces' occupancy, etc.), classifiable also into territorial and building reports, depending on the level of information visualizable. Each report is correlated to the others based on a predefined structure (Fig. 1), but still independent, allowing to introduce different accessibility levels according to the requesting user.

3. RESULTS AND DISCUSSION

The proposed methodology and AMS-app are being applied as a pilot study to the UniTO asset management, as described in the following sections.

3.1 UniTO pilot case

3.1.1 Main objectives and needs definition

UniTO aims to create an integrated AMS-app that enables updated data visualization to optimize the management of its diffused asset, providing information about performance and resource utilization, to promote cost reduction and improve efficiency. The main goal consists in improving the management of spaces and resources. The AMS-app enables to identify and monitor the asset over time, leading to better decision-making concerning space, occupancy, and IEQ management. It was applied to digitalize the whole UniTO building stock, providing an overall view with data about its consistence and usage (i.e., geolocation, building asset consistency, geometrical and financial data, building performances, rooms capacity, equipment, and performances, occupancy level, and usage, etc.). The updated visualization of the building portfolio through a 3D map with data and information handled through GIS, BIM, and BI systems aims to support the:

- Management of university facilities at the territorial and building levels allowing to produce data analytics at different layers for improved facility operation;
- Optimization of university teaching timetables based on the actual teaching space availability and capacity;
- Optimization of workstations management by introducing remote working strategies;
- Analysis and optimization of IEQ to improve users' comfort and safety through IoT monitoring.

3.1.2 Current database structure and dataflow management strategies investigation

Currently, the university technical areas handling data and documentation about facilities, spaces and related equipment, performance, capacity, workstations' number, and concerning the teaching timetables' definition, rely on a document-based system characterized by siloed information. Data about spaces and related usage are stored and exchanged via semi-structured formats such as .xls or .csv. Information exchanges take place mainly via traditional communication systems (printed reports, e-mails, calls, in-person or remote meetings, etc.), and data are not shared between stakeholders or administrative offices, resulting in struggling or absent analysis of integrated aspects and information to support the decision-making processes. Thus, a data integration system is proposed with the aim of creating an updated tool collecting data from several sources, shared among the whole UniTO staff. The different data silos are integrated by exploiting BI tools and methods, enabling to collect and integrate data from the various Excel sheets produced by the technical areas. In this way, it is possible to maintain the current processes adopted to manage space, staff, and usage data, avoiding disrupting the management procedures. Furthermore, it is possible to avoid the effort of creating a structured DB (e.g., a relational SQL database) that would have been more disruptive and difficult to integrate within the UniTO management system. This allows for the gradual and low-impact integration of the AMS-app and the system, with a greater likelihood that it will be concretely used by UniTO staff.

3.1.3 Organization information exchange and information requirements formalization

The data integration system has been set up by a cross area within the UniTO organization represented by a research group of seven people which acts as a data analysis area. The authors are part of this research area that collects the different data from UniTO areas integrating them through the proposed system (AMS-app) according to the schema illustrated in Figure 2.

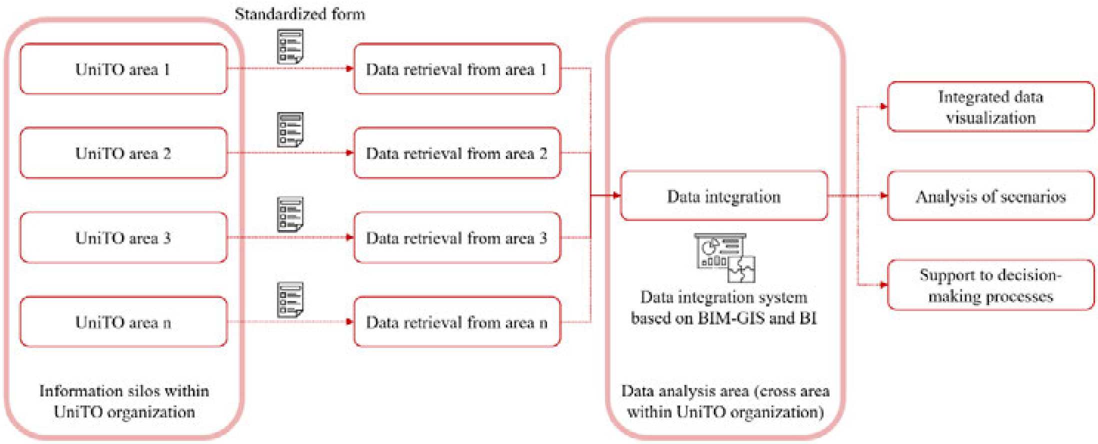

Fig. 2: Information exchanges and data processing schema within UniTO organization.

Data are retrieved from UniTO technical areas via standardized forms (Table 3), and the data analysis area receives information concerning buildings, spaces, capacity, occupancy, people occupying the spaces, etc. through similar forms. This enables quick data management via structured data sheets and avoids the cleaning and processing of data first. The integrated data, the resulting information, and knowledge are made available and displayable via the platform, enabling scenario-based analysis to support the decision-making processes of the UniTO's asset management staff.

Table 3: Example of standardized form for collecting data about some of UniTO facilities, collected in the.

Building code	Building name	Main address	Municipality	Main use	Building type	Status
001_A	Palazzo del Rettorato	Via Verdi 8	Torino	"Uffici a supporto didattica e ricerca	Fabbricato	In uso
020_A	Palazzo Nuovo	Via Sant'Ottavio 20	Torino	Dipartimenti / Biblioteche / Aule / Uffici a supporto didattica e ricerca	Fabbricato	In uso
021_A	Palazzetto Aldo Moro	Piazzale Aldo Moro	Torino	Uffici a supporto didattica e ricerca / Aule / Dipartimenti	Fabbricato	In uso
029_B	Campus Luigi Einaudi	Lungo Dora Siena 100	Torino	Dipartimenti / Biblioteche / Aule / Uffici a supporto didattica e ricerca	Fabbricato	In uso
032_A-B-C	Centro Pier della Francesca	C.so Svizzera 185/Via Pessinetto 12	Torino	Dipartimenti / Aule / Magazzino / Rimessa / Uffici a supporto	Porzione di fabbricato	In uso
064_A	Torino SUISM	Piazza Lorenzo Bernini, 12	Torino	Aule/Uffici a supporto didattica e ricerca	Fabbricato	Dismesso

Specific applications of the proposed data integration system and AMS-app are described in the following sub-sections, including advantages and limitations. The case study selected as a demonstrator for such applications at the building level is the Campus Luigi Einaudi (CLE). The main facility of CLE is located in the northeast area of Turin, with a total net area of more than 36,000 square meters. The facility hosts the Department of Law, the Department of Political and Social Sciences, and the Department of Economics and Statistics "Cognetti de Martiis", hosting more than 500 research fellows. In addition, there are numerous administrative areas with around 100 administrative employees dealing with the management of spaces, people, contracts, and related bureaucratic matters. Furthermore, the CLE has 47 lecture halls and hosts around 16700 university users, so it represents a significant case study with a large catchment area and many activities within it.

3.2 Real estate asset management at territorial level

Real estate asset management at the territorial level deals with the storing and managing of data concerning the location, the type of building property (e.g. owned, rented from another institution or a private subject, partially owned or partially rented, etc.), the overall occupancy, the presence of listed buildings, and other facility management data. This kind of data regarding UniTO facilities currently are stored in siloed documents or .xls files, preventing the integrated analysis needed to support decision-making processes. Thus, overall dashboards regarding the whole UniTO's real estate property are produced to investigate multiple data at once. The dashboard maps provide an overview of the entire territory over which UniTO buildings are distributed, useful to investigate data at a territorial level. All the views provided on the dashboard pages (e.g., maps, charts, graphs, and cards) are dynamic and interactive. A selection in one view, acts as a filter for all other views of the page or of the entire dashboard report, according to the specific requirements. The dashboards at the territorial level support the decision-making processes regarding the strategies to be pursued at a high level on the whole university facilities.

Figure 3 shows the dashboards at the territorial level with general data regarding UniTO real estate propriety. Other information, such as UniTO facilities under refurbishment and data concerning specific interventions or the listed buildings are visualized in other tailored dynamic dashboards, allowing an integrated analysis of the data and supporting complex decisions of the UniTO's administrative areas.

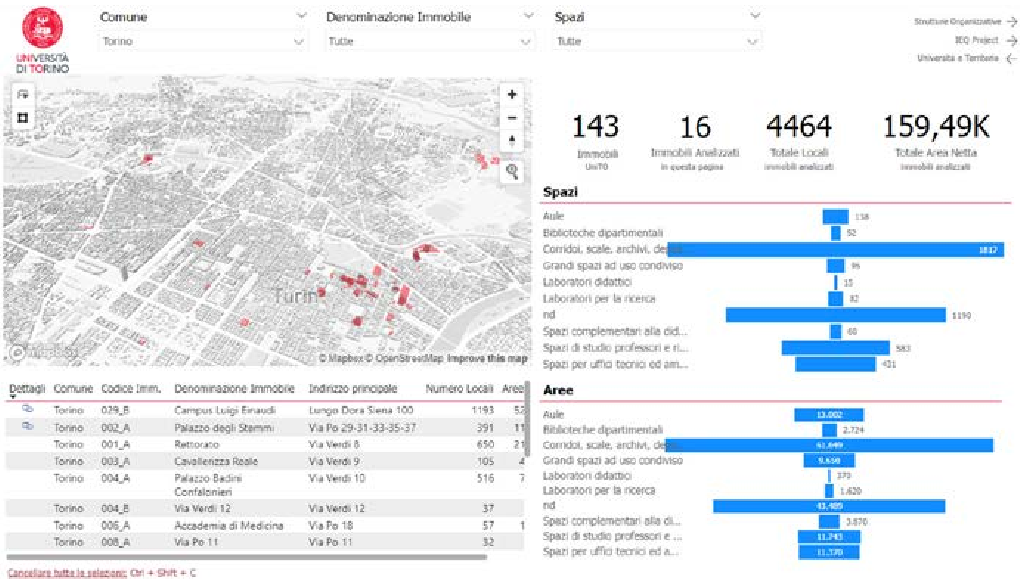

Fig. 3: AMS-app dashboard at territorial level regarding general data of UniTO real estate propriety.

3.3 Lecture hall spaces and teaching timetable management

Managing teaching spaces and, specifically, organizing lesson timetables, poses a multifaceted challenge. The problem is intricate due to the numerous and diverse variables involved, especially concerning CLE. Notably, the presence of various departments and their distinct methods of allocating the timetable adds to the complexity. Additionally, the extensive range of teaching hours dedicated to different subjects and the diverse nature of activities carried out further necessitate a highly varied schedule even within the same building.

The current process for creating class schedules and allocating spaces seems to be structured in stages, with three distinct directorates/offices involved. Firstly, the "*Educational Services Directorate*" supplies information regarding course enrolments, course codes, and academic credits assigned to each course. This data is then passed on to the "*Degree programs office*" which operates under the school's guidance, serving the departments and is tasked with creating the teaching timetable. Finally, a local branch of the "*Building Logistics and Sustainability Directorate*" is responsible for space allocation based on the received teaching timetables.

The entire process is characterized by fragmented data handling and manual switching between different software, which could increase the risk of errors. Thus, the primary objective was to consolidate the data into a single data analysis platform, ensuring more secure management and facilitating the analysis of teaching space utilization. To achieve this goal, a dashboard was developed, providing a comprehensive view of various data that would otherwise require gathering from three different offices. This single dashboard allows users to access information about the teaching spaces, including classroom names, room codes, capacity, classroom equipment, and net area. Moreover, the dashboard also offers insights into space utilization and teaching hours, enabling the estimation of the percentage of hours during which classrooms are booked, optioned, or available for use. This centralized and user-friendly approach streamlines data access and analysis, enhancing overall efficiency and accuracy in managing teaching spaces. Figure 4 illustrates the flexibility of viewing rooms in both 3-dimensional and 2-dimensional formats. Regardless of the chosen view, users have the option to select specific rooms and access detailed data. The interactive line graph enables direct interaction with the data, and users can also apply filters based on the building's floors. At the room level, the scheduled time for each room throughout the week, month, or year can be displayed, as depicted in Figure 5.

Fig. 4: AMS-app dashboard at building level with the analysis of lecture hall spaces and occupancy.

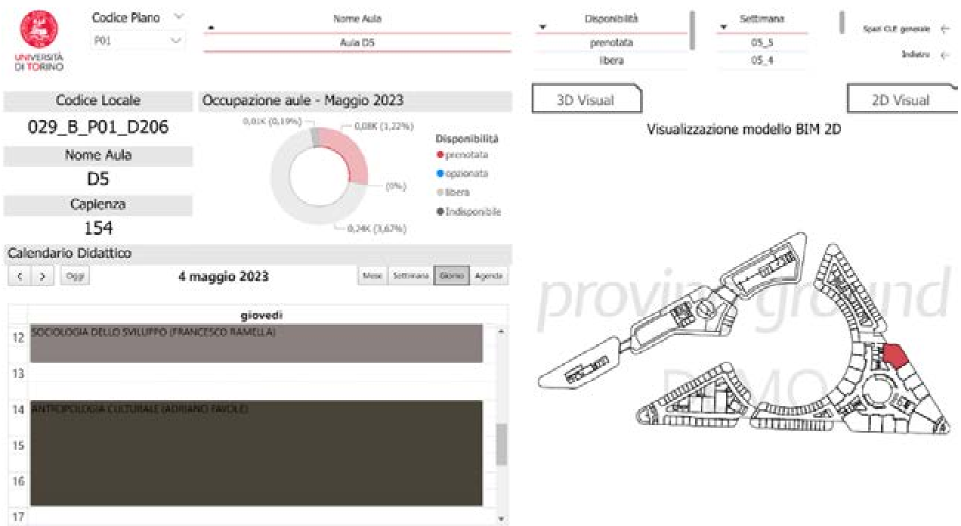

Fig. 5: AMS-app dashboard at room level allowing the analysis of lecture hall spaces, occupancy and timetable.

3.4 Real estate asset management at building level

Real estate asset management at the building level refers to multiple activities necessary to operate a facility and can include the following: people management including contract management, space and equipment allocation; space management including space allocation to the departments and areas hosted in each building. As of now building operation at UniTO is performed by the same departments or administrative staff hosted in each facility.

Except for space codes, the structure of which is common to all UniTO administration, all other space management information is managed locally by each building's space management staff. There is no central structure that manages all UniTO facilities at the space level.

The main objectives of this application are to support the decision-making processes regarding UniTO facilities, collect all the necessary information, and produce dashboards at the building level to investigate space, occupancy, and people management via BIM-GIS integration and BI technology. The data that are treated are the following:

- Space data regarding the location inside the building, area, and space typology;
- Allocation of spaces to the departments or administrative areas;
- Allocation of spaces to specific people and their role inside UniTO, contract typology, affiliation to a department or administrative area.

Figure 6 and Figure 7 show the AMS-app dashboard at the building level regarding all the spaces of CLE and the specific analysis of occupancy and staff allocation in the offices respectively.

Figure 6 allows the analysis via dynamic maps and charts of the spaces in terms of space typology and number of rooms, the allocation of the spaces to the departments or administrative areas, and single data points concerning the space net area and the number of rooms. The page allows the overall analysis of the building and the consultation of the general data regarding spaces, as well as the distribution of the space typologies on each building floor and the summary of the total building net area and number of rooms.

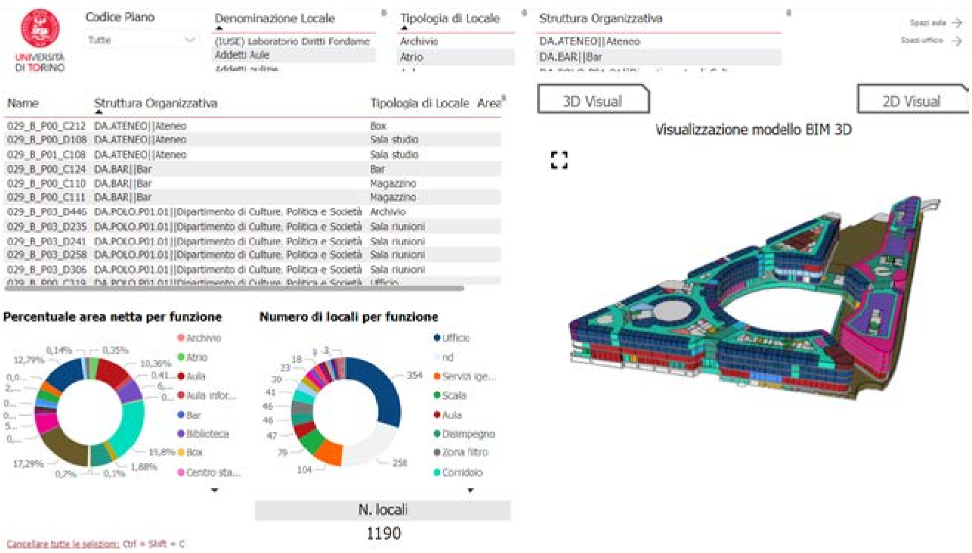

Fig. 6: AMS-app dashboard at building level allowing the analysis of space features and allocation of CLE.

Figure 7 enables a more specific analysis of the offices at CLE, including the percentages of area and staff assigned to each department and administrative area. A graph allows the comparison among the employee and research fellows allocated to the spaces and the maximum number of people that can be hosted according to the net area of each room, supporting the decisions related to the new staff that can or cannot be allocated in a space. In addition, an equal distribution of the spaces among departments and areas can be ensured based on the analyses

Fig. 7: AMS-app dashboard at building level with the detailed analysis of office and staff allocation at CLE

3.5 Space management improvement

Space management improvement in UniTO pilot case refers to the study of strategies to improve space occupancy, allocation, and usage with the introduction of work from home (WFH) practices. The contracts of professors, research fellows and PhD students already include flexibility as regards working hours and location, consequently, WFH is already allowed. On the other hand, concerning administrative employees, WFH practices have been introduced due to the recent COVID-19 pandemic events and then maintained for a total of two days a week. However, as of now, no improvement in space management has been introduced related to flexible work scheduling.

This application of the UniTO AMS-app aims at improving space management by hypothesizing a homogenous distribution of WFH days of the employees/researchers of the same office over the working week. As a consequence, the maximum occupancy of a single office can be increased. All the occupants are never present in the office at the same time, while WFH days are planned so that in each day of the week a certain number of office occupants work at home. As a results, the overall occupancy in a building can be increased. Considering two days a week of WFH for each worker in a five-day working week, the overall occupancy of the building increases by around 60% (Figure 8). This ensures that in the case of recruitment, workstations are already available in the existing facilities, without the need of acquiring or renting new spaces.

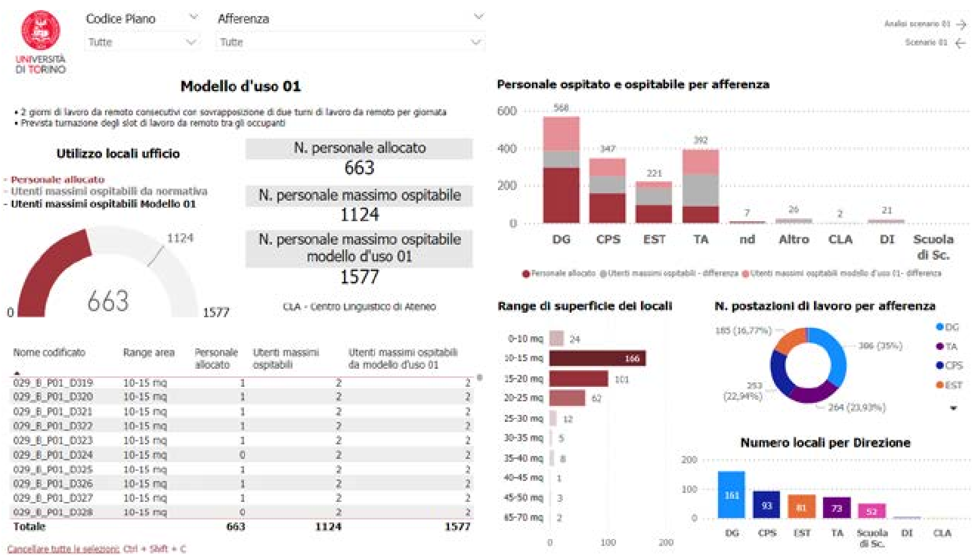

Fig. 8: AMS-app dashboard analyzing space allocation and current number of occupants, the maximum capacity of each space, and the maximum one with WFH and strategies to improve CLE space usage.

3.6 Indoor environmental quality monitoring and optimization

Monitoring data related to environmental quality data monitoring within educational spaces is of utmost importance. It serves two primary purposes: ensuring a healthy learning environment for conducting lessons and detecting any anomalies that may indicate system faults or the need for system remodeling. This approach also contributes to energy conservation and the reduction of heating and cooling systems' emissions. Over the past two years, several UniTO's buildings have been equipped with IEQ sensors. Among these, the CLE buildings serve as an excellent testing ground for evaluating the effectiveness of these systems due to the high number of sensors and the presence of classrooms with different capacities and orientations. UniTO has chosen IoT devices from Aircare® that can capture 15 types of measurements, including air quality, environmental comfort, and electro-smog indicators. Notably, the devices' accuracy and reliability have been scientifically validated by the Italian Society of Environmental Medicine (SIMA) for PM2.5 and CO2 measurements. A total of 39 IoT devices were strategically installed across 37 classrooms within the CLE, focusing on the ground and first floors, dedicated to teaching activities. Once installed, the data generated by these devices was directly streamed to a cloud platform, facilitating data collection. The collected data are accessible through reports, providing valuable information via an experimental platform managed by the ICT directorate, and at this stage data aren't shared publicly or with other directorates.

The objective was to optimize the AMS-app potential by linking the data to specific spaces and creating interactive dashboards to display real-time data from the continuously flowing information from the IoT devices. To maximize the advantages of measuring multiple types of data with a single IoT device, it was decided to associate viewable spaces with data related to CO2, CO2e, VOC, PM10, and PM2.5. A dashboard was developed to integrate the data with floor plans, clearly indicating the locations of installed sensors in the respective classrooms. By selecting a specific classroom, users can readily access and visualize the recorded values throughout the week (Figure 9).

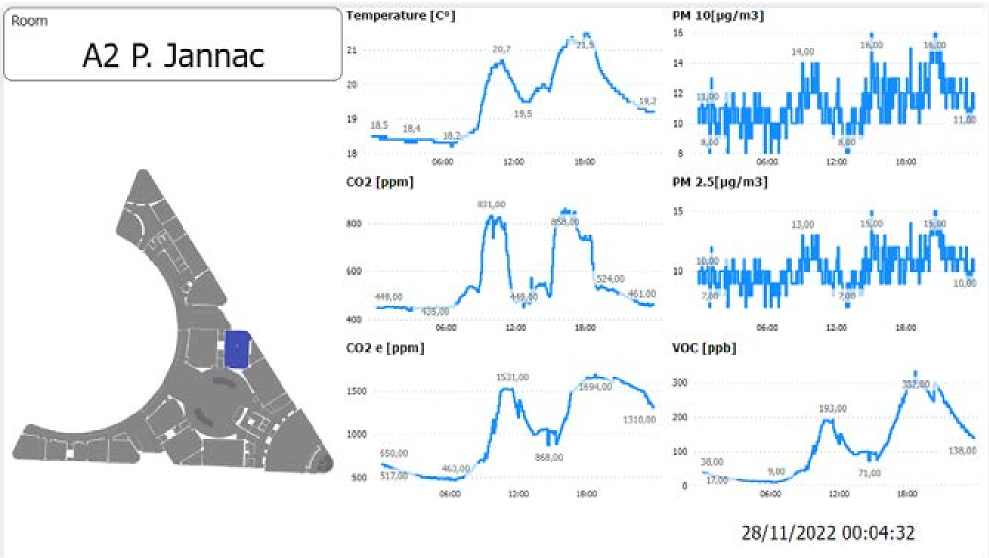

Fig. 9: AMS-app dashboard at room level allowing the visualization of spaces and data acquired from sensors.

To serve as alert indicators, specific limit values were established for the main parameters. During the heating season, temperature values between 20 and 22 degrees Celsius were selected, while for the cooling season, the range was set between 22 and 24 degrees Celsius. The CO_2 concentration threshold was defined at 1000 parts per million (ppm). As for particulate matter, the limit values suggested by the World Health Organization were adopted: below 25 µg/m^3 for PM_{10} and below 50 µg/m3 for $PM_{2.5}$. Furthermore, for volatile organic compounds (VOCs), the limit of 550 parts per billion (ppb) was chosen, following the guidelines of the US Environmental Protection Agency (EPA). This solution offers various advantages: firstly, it allows immediate visualization of the data collected by IoT devices and their correlation with specific spaces; secondly, it facilitates the analysis of recorded anomalies in relation to occupancy and class schedules of those spaces. This comprehensive approach provides valuable insights for maintaining a healthy and optimized teaching environment.

4. CONCLUSIONS AND FURTHER DEVELOPMENTS

The paper illustrated the research conducted under the umbrella of the UniTO's strategic plan, aimed at developing an AMS-app to optimize the management of one of the largest university assets in Italy. The replicable methodology developed for the definition of the app and its implementation in the organizational system was illustrated. The BIM-GIS-BI integration enabled to systemize the various information currently siloed managed, providing an integrated decision-support tool accessible starting from the territorial level to the single building and component. Through the illustration of several case studies implemented so far on selected buildings, the potential of this management system was illustrated, also highlighting the difficulties encountered and the margins for improvement. Such a system is easily replicable and showed true potential in being able to manage the available resources optimally and consciously. Both in terms of space and economics, it also allows for the optimized management of facility services and improved IEQ performance for the end-user experience, leading to effective and sustainable management. In the future, information protocols and guidelines will be developed for the proper adoption of such an AMS and the correct definition of the IRs. Furthermore, it is envisaged that the management processes currently underway will be reviewed in consultation with the heads of the technical-administrative areas aiming at the optimal adoption of the system, as well as the implementation of a data-sharing system exploiting a data lake from which to extrapolate the targeted information, identified based on the management processes and the defined IRs.

ACKNOWLEDGEMENTS

The authors thank the University of Turin for the case study and the availability of both administrative offices and technical areas. A special thank also to the colleagues Mirko Locatelli, Laura Pellegrini, Marta Boscariol and the BIMgroup lab from Politecnico di Milano for the participation and support.

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TOWARDS A FRAMEWORK FOR RAILWAY NETWORK ASSETS MANAGEMENT BASED ON BIM/GIS INTEGRATION

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ABSTRACT: *Complex infrastructures such as railway networks face increasing challenges related to resource allocation, external events, constraints, and demands. Therefore, it is crucial to optimize the Asset Management (AM) phase to ensure the value and functionality of the assets. The integration of Building Information Modelling (BIM) and Geographic Information Systems (GIS) can support this phase, but it can only yield benefits with a comprehensive approach that considers and addresses the specific needs and resources of the assets and their AM organization. The main benefits include improved data management, manipulation, information visualization and optimized resource allocation. This study describes an intermediate step towards developing a BIM/GIS integration framework for AM that can guide both researchers and practitioners. The framework aims to bridge theory and practice by incorporating insights from literature reviews and case studies. Its main objectives are to provide a comprehensive multi-stakeholder view and methods for effectively integrating BIM and GIS in this context. To develop the framework, the study employed focus groups, interviews, and practical BIM/GIS tests, which provided insights reported in this article. Furthermore, the study provides research directions for effective BIM/GIS integration in infrastructure AM.*

KEYWORDS: *Building Information Modeling, BIM, Geographic Information Systems, GIS, BIM/GIS integration, Asset Management, Railway*

1. INTRODUCTION

Railway networks, like other complex infrastructures, are affected by manifold challenges. Given their significance for societal improvement, they must provide increasingly high-quality services (Famurewa et al., 2015) while coping with external factors such as extreme weather and resource management (Garmabaki et al., 2021). Moreover, railway networks function as intricate systems, requiring adoption of complexity-based approaches in order to achieve effective management (Oughton et al., 2018). The improvement of the tools, processes and information management during the Asset Management (AM) phase and the Operation & Maintenance (O&M) phase is a key factor to address these issues and to implement an effective management of railway networks. O&M represents one element of the broader concept of (AM), which is defined as "the coordinated activities of an organization aimed at generating value from assets" (ISO, 2014). The O&M phase, being focused on the operational and maintenance aspects of the asset is commonly considered as a part of the whole AM phase, in which also strategical and tactical decisions about the owned assets are addressed (e.g., investments, risk management etc.). In particular, for infrastructure such as railways, a systematic approach is required in order to properly manage the assets and to avoid resource waste which would affect the benefits provided to society (Almeida et al., 2022). According to the National Institute of Standards and Technology (NIST), approximately 60% of the total life costs of built assets are accounted for in the O&M phase due to inadequate interoperability, leading to considerable wasted resources on information retrieval and poor data management (Gallaher et al., 2004).

As a technical solution, the integration of Building Information Modeling (BIM) and Geographic Information Systems (GIS) has been widely addressed both in literature and in practice. BIM is a widely adopted methodology that encompasses the entire AECO/AM sector (Architecture, Engineering, Construction, Operation, and Asset Management) and the complete life cycle of a built asset. BIM aims to promote collaborative processes and prevent information loss between phases, such as from construction to the AM phase. By means of parametric 3D models and standardized workflows and information exchanges, BIM allows to implement digital built environment asset management (Re Cecconi et al., 2017). BIM aims to address cost reduction and optimize related tools and processes. However, for effective BIM adoption in AM, asset owners and managers (in the role of appointing party as defined by ISO 19650) need to carefully assess which information and BIM uses are required. This process involves the definition of several requirements, as specified in ISO 19650, such as OIR, AIR, EIR, and PIR (Organizational, Asset, Exchange, and Project Information Requirements) (BS EN, 2019). In the context of AM, OIR and AIR serve as the primary sources of requirements for delivering the AIM (Asset Information Model),

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Mattia Mangia, Carla Di Biccari, Mattias Roupé, *Towards a Framework for Railway Network Assets Management Based on BIM/GIS Integration*, pp. 431-442, DOI 10.36253/979-12-215-0289-3.42

derived from the PIM (Project Information Model). For most AM processes, 3D geometries become less relevant, while non-geometric data related to the asset, e.g., warranties, installation dates, etc. are more important. Furthermore, organizations managing infrastructures deal with diverse assets, including both punctual buildings and horizontal infrastructures like railways, roads, and pipelines. Infrastructural AM can benefit especially from BIM/GIS integration, due to the specific need of multi-scale approaches (Breunig et al., 2017). In fact, while BIM may provide detailed data about the asset itself, GIS complements it by representing data at larger scales. The aim of this research is to investigate and address the needs of railway network management through business-oriented BIM/GIS integration for AM. To link literature with practice, the final goal of the entire research is to provide a framework based both on current theories and the findings from case studies. The construction of the framework was guided by the following research questions:

- Which is the current status of BIM and GIS implementation by organizations in charge of AM of the railway network?
- Which are the main benefits and hindrances of BIM/GIS integration for the AM of complex infrastructures such as railway networks?
- How BIM/GIS integration should be implemented according to the business core of the organization in charge of AM of railway networks?

At the current state of the research, results from an Italian case study are presented. The subject of the case study is RFI (Rete Ferroviaria Italiana), a large public company responsible for managing the railway network in Italy. The case study was conducted through Focus Groups and semi-structured interviews. Subsequently, practical tests of both BIM and GIS software have been performed and discussed in order to highlight theoretical and practical implications of BIM/GIS integration for AM in the railway context.

1.1 Background

1.1.1 BIM/GIS integration

BIM/GIS integration is a topic that has been deeply investigated in recent decades due to its acknowledged multi-purpose potential. A key point of the topic is that methodologies for integration may vary significantly, occurring at different levels and with different tools (X. Liu et al., 2017). Moreover, BIM/GIS integration is affected by several issues and challenges at the geometric and semantic levels. Several methods, frameworks, and software prototypes have been proposed for different applications, such as flood damage assessment (Amirebrahimi et al., 2015), web-based bridge management (J Zhu et al., 2020), infrastructure asset management (Garramone et al., 2020), etc. In terms of semantics, a promising approach found in literature is the adoption of semantic web technologies, ontologies, and Building Linked Data (Pauwels et al., 2017). Liu et al. (X. Liu et al., 2017) proposed a ranking of the several BIM/GIS integration methods classified by EEEF criteria, namely Effectiveness, Extensibility, Effort, and Flexibility. Addressing these criteria is crucial because the choice of a BIM/GIS integration path depends on the needs of the specific case and context. According to these criteria, semantic web technologies have been ranked with a “high” score in Effectiveness and Extensibility, but also a “high” amount of effort required for the implementation. These criteria imply a cost/benefit analysis which is necessary for effective BIM/GIS integration. Linked to this matter, another recurrent trend found in literature is the almost forced adoption of commercial software for effective BIM/GIS integration. In fact, the adoption of ArcGIS PRO is recurrent, along with the one-directional approach “BIM to GIS” for data integration (Ma & Ren, 2017). Regarding the complex conversion of BIM to GIS files, FME software is also a solution frequently found in the literature (Junxiang Zhu et al., 2019). However, important efforts found in literature foster open-source approaches and tools (Jiang et al., 2019), because they may provide support to address the increasing complexity of projects, the need for better interoperability and the need to mitigate costs. Among relevant open-source tools, Cesium is an open platform for 3D geospatial data that may implement a 3D BIM/GIS environment (F. Liu et al., 2020), as long as BIM models are converted to other formats such as .gltf or .obj. The literature shows that BIM/GIS integration is a complex and multifaceted topic, which requires an in-depth contextual analysis. For this reason, this research attempts to contribute by providing a framework based on knowledge obtained not only from literature but also from specific case studies. Besides the technical challenges, BIM/GIS integration is also an organizational cultural and competence shift, thus it should be addressed according to the specific needs of companies and involved stakeholders.

1.1.2 Asset Management and BIM/GIS integration for infrastructures

When compared to previous phases such as design and construction, AM and the O&M phase are affected by peculiar theoretical and practical gaps when related to BIM. One of the reasons is that the object-oriented paradigm and the parametric approach provided by BIM authoring software tools are less straightforward to utilize in the context of AM. On the other hand, given that AM is facilitated by IT systems, leveraging BIM for automated information exchanges holds considerable promise and potential benefits. Furthermore, the primary standard for AM, namely the ISO 5500x collection (ISO, 2014), does not directly address BIM methodology. Instead, it relies on ISO 19650-3 (BS EN, 2019) as the main reference source. In comparison to GIS, BIM is relatively recent and lacks shared and well-standardized paths for AM. Several factors contribute to this situation. Firstly, AM suffers a lack of a structured framework of BIM standards and tools (Munir et al., 2019). Secondly, the IFC (Industry Foundation Classes) data model has only recently been updated to consistently represent railways with the IFC 4.3 schema release (buildingSMART, 2022). Lastly, the specification of OIR and AIR poses challenges for asset management companies due to unclear role of BIM in supporting their core activities (Hadjidemetriou et al., 2023). The conjunction of these factors hinders BIM or BIM/GIS adoption, with the risk to implement an ineffective change management from traditional to BIM-based AM (Jupp & Awad, 2017) thus nullifying the benefits of BIM adoption and resources invested (Dixit et al., 2019).

Despite the challenges of BIM/GIS integration, the literature still agrees on its need and expected benefits. For instance, BIM-based information exchange and storage standards may ease information retrieval and management, meanwhile GIS may provide analysis tool for the whole asset portfolio and its relation with environment and surroundings (Wang et al., 2019). However, fully unlocking the potential of integrating BIM/GIS for infrastructure AM requires a more in-depth investigation across strategic, tactical, and operational levels. The entire potential of BIM/GIS integration for infrastructure AM needs to be further explored at these levels (Garramone et al., 2020). Existing literature and available tools illustrate a promising scenario for achieving and effectively implementing BIM/GIS integration. To the best knowledge of the authors, in the current literature, organizations' awareness of possible benefits given by BIM-based AM approaches and solutions is not sufficiently considered, especially in the specific context of railway networks. To address this gap, this research aims to offer insights from an organizational perspective while conducting technical evaluations of both commercial and open-source alternatives.

2. MATERIAL AND METHODS

To answer the aforementioned research questions, a broader research has been undertaken as a multi-step process, of which a brief overview is provided in Figure 1.

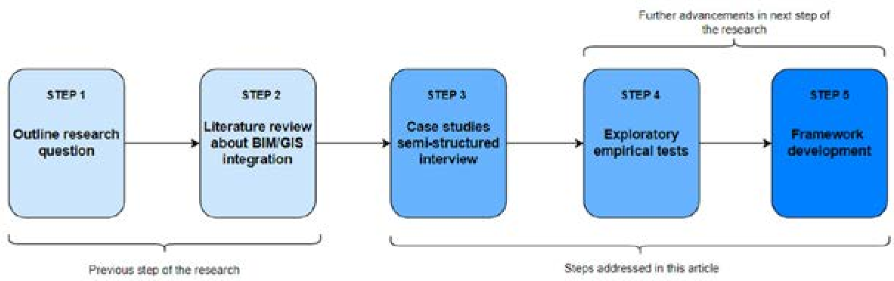

Figure 1 Overview of the multi-step research.

The work presented in this article follows a systematic literature review (SLR) concerning BIM/GIS integration (Mangia et al., 2022). Building upon the findings from this initial step, the focus was subsequently narrowed down to a specific life-cycle phase and asset class, namely the AM phase and transport infrastructures. Following this, two case studies (involving RFI and Trafikverket, respectively) have been conducted to answer the research questions. In this work the RFI case study is presented, and case study methodology is defined as an in-depth investigation of a particular subject, such as a group, organization or phenomenon in a real-life context (Crowe et al., 2011). The case studies have been addressed by means of four main activities:

1. Data collection by means of semi-structured interviews (SSIs) and focus-group;

2. Data processing;
3. Tests and experiments with several BIM and GIS-based software;
4. Evaluations of the key elements of a framework for business-oriented BIM/GIS integration.

Data collected in activity 1 are mainly related to the following two topics:

- Existing AM, GIS and/or BIM systems employed by the company;
- Awareness of benefits obtainable from BIM and BIM/GIS integration for the business core of the company.

Activity 1 was carried out across multiple sessions. The Focus Group method was selected as it facilitated the involvement of RFI departments interested in BIM/GIS integration and allowed confirmation of the authors' hypothesis: "BIM is not yet a well-established tool adopted in the core business and it lacks a standardized integration approach with existing systems." The focus groups engaged personnel from various RFI departments that could potentially be impacted by BIM/GIS integration, such as AM/ERP system users and administrators, GIS users, and others (Table 1). The researchers, acting as focus group facilitators, were able to provide a common and shared understanding of BIM/GIS integration opportunities and limitations and to receive feedbacks from different perspectives.

Table 1 List of participants of focus groups and interviews.

Department	Executive Manager	Maintenance management	InRete.2000 system support	MUIF support	Asset Management
Interviewees	N°1	N°2, N°3, N°4	N°5, N°6	N°8, N°9	N°10, N°11

In addition to this, semi-structured interviews were conducted with each business unit to delve deeper into the investigation and to pose specific technical and organizational inquiries to each interviewee. The "Data processing" activity involved the analysis of the information retrieved from the Focus Groups, interviews and related documentation provided. Knowledge about company-level standards, demonstrations of existing systems and datasets were provided for processing. This led the authors to the "Tests and experiments" activity, in which a series of exploratory experiments with several BIM and GIS software and tools were performed. The objective of these tests was to identify and assess a list of "key-elements" which the framework should address (i.e., the fourth activity of this research). For the tests and experiments, QGIS was employed for inspecting and extracting data from the geodatabase provided by RFI. Autodesk Revit and Bentley OpenRail Designer were used as BIM authoring tools to create simple 3D models of different types of assets (such as buildings, railway tracks, and sidewalks). Autodesk InfraWorks was utilized to present a 3D BIM/GIS environment for Proof of Concept (POC) purposes. The IFCjs and ifcopenshell software libraries are currently under test in order to extract data from IFC BIM models and evaluate web-based BIM/GIS viewers. Taking into consideration the outcomes of focus groups, interviews, and software tests, the final step of the broader research will concentrate on developing the framework for BIM/GIS integration for AM.

3. RESULTS

In this section the results obtained in the scope of the Step 3 and 4 reported in Figure 1 are reported. These results provided the conceptual and practical foundations which drive the ongoing development of the framework (i.e., Step 5) discussed in Section 4.

3.1 BIM potential for existing systems

One of the pivotal results for the development of the framework is the identification and analysis of existing systems. This information is one of the two main results retrieved from the Data Collection and the Data Processing activities. The second main result is addressed ins sub-section 3.2. RFI adopts two primary information systems for AM that have potential for integration with BIM. The authors were presented with comprehensive demonstrations of these systems during the interviews. The examination of the systems currently utilized by RFI supplied essential insights for assessing BIM/GIS integration options and addressing the initial research question.

A schematic overview of the two main systems is provided in Table 2.

Table 2 Overview of the two RFI system investigated.

System	Type	Data involved	Tasks performed
InRete.2000	ERP	SeTe's data model, master data sheets	- Translation of infrastructure projets into a railway network model composed of locations and routes. - Censorship the railway network assets by means of a compiled master data sheet (e.g., train stations, railways). - Management and maintenance tasks of every asset of RFI (e.g., asset is in function or surpressed, failure management etc.).
MUIF	WebGIS	Geodatabase consisting of 2D GIS layers, DTMs photospheres and 3D pointclouds.	- Context and asset visualization at the macro-, meso- and micro-scale. - GIS spatial analysis (e.g., buffer zones). - Bi-directional linkage with other RFI systems for AM and O&M (e.g., route interruption).

The first system is InRete.2000, a customized version of SAP AM software. It is an Enterprise Resource Planning (ERP) software which supports the management and maintenance of the railway network infrastructure. Based on RFI data model, assets managed with InRete.2000 are represented by means of two entities, namely called "Sede Tecnica" (SeTe) and "Equipments". SeTe entities serve to represent spatial structures or components that require maintenance, such as train stations and tracks. "Equipments" refer to physical objects installed within SeTes. Each SeTe and Equipment is assigned an ID within InRete.2000, referred to as the "Code of Sede Tecnica," which establishes semantics and hierarchy among the assets. Information within a SeTe is populated through on-site surveys, manual checks, and operator input. A SeTe is composed of sets of data and metadata, such as its location, working status, maintenance activities etc. In InRete.2000, a SeTe's record acts as a master data sheet for the respective entity. The hierarchical decomposition of SeTes mirrors the network model adopted by RFI. In particular, the railway network (which is a SeTe of first level) is characterized by two main elements: "Località" (Locations, code LO0000) which constitutes the nodes and "Tratte" (Routes TR0000) as the edges of the network.

Presently, InRete.2000 lacks geometrical and geographical visualization for SeTes, which is instead provided by MUIF (Modello Unico dell'Infrastruttura – Unified Infrastructural Model) in the form of a web-GIS application. MUIF is a long-term project initiated to establish a common information system supporting the business logic of each department of RFI. MUIF encompasses information about all assets within the rail network managed by RFI, facilitating the tracking of related data, visual representation of asset physical aspects, and verification of their geographic locations. The geodatabase predominantly comprises shapefiles, Digital Terrain Models (DTM), photogrammetric data sources like point clouds and orthophotos. Both InRete.2000 and MUIF are firmly established as essential tools for RFI, supporting their core business functions. These systems enable activities such as failure management, maintenance orders, route interruptions, and more. The former is employed for the management and maintenance of the railway network, and at the current state it is bi-directionally linked with MUIF by means of the hierarchical ID named "Code of Sede Tecnica". In addition, MUIF users may inspect a part of the railway network by means of photo-spheres and point clouds as shown in Figure 2. However, the 2D maps and the 3D point clouds are displayed in two distinct frames within a browser page, thus a unified 3D web GIS environment is not implemented yet. According to the interviewees, BIM holds potential for integration with existing systems, since it could significantly improve several processes such as context inspection and information retrieval. With BIM, detailed asset-level 3D models and information could be readily accessible, both for large entities as SeTes and for small ones like Equipments, which can be challenging to represent in MUIF despite their presence in InRete.2000. Moreover, the hierarchical data model of assets managed can be reflected in BIM components with dedicated attributes, which needs to be specified by RFI in its AIR. Working as an ID, these attributes may also partly overcome the needs of semantic which will be provided by the release of the new IFC 4.3 version.

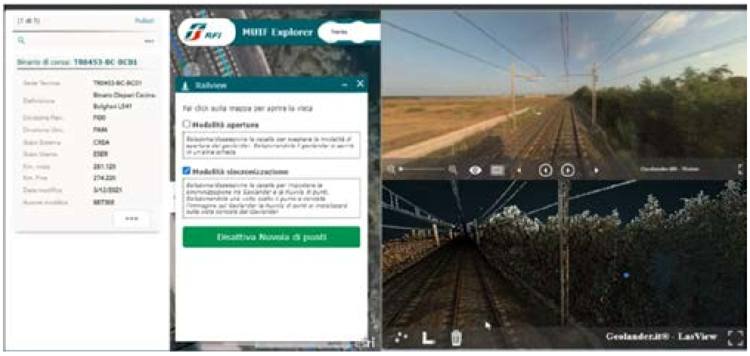

Figure 2 Screenshot of MUIF point clouds and photospheres to integrate the 2D GIS environment.

3.2 BIM and GIS state of the art in the organisation

The interviewees provided a comprehensive and multi-perspective overview of the current status of BIM and GIS within the organization. From the analysis of the Italian case study, as the second main result of the Data Collection and Data Processing activities, the researchers identified key concepts that need to be considered for the development of the framework:

- BIM: While existing systems have not yet fully integrated BIM, the organization actively participates in various BIM pilot case studies and work groups to test and implement BIM led by buildingSMART initiatives;
- The existing systems are undergoing continuous strategic development, making disruptive software changes impractical. Therefore, BIM should be integrated into the existing systems without severe changes to the system architecture;
- Several commercial vendors of AM systems already offer BIM-plugins in the AM environment, including SAP;
- Asset management personnel currently lack autonomous access to relevant data and technical drawings of assets (e.g., plants, sections), where AIM CDE linkage could provide support;
- BIM data and models can enhance several manual processes, such as InRete.2000 datasheet filling and on-site inspections;
- Organizations involved in AM of infrastructures are typically large, and implementing changes and processes can be costly and time-consuming;
- Vendor-agnostic approaches for information exchange, like OpenBIM, are vital since these organizations will mainly receive BIM-based data in open formats such as .ifc or COBie-compliant datasets. It also supports BIM/GIS integration thanks to IFC model conversion to 3D GIS formats;
- The prevailing notion regarding BIM models is that they become static data sources stored in the AIM CDE after project handover. However, there is potential for dynamic BIM utilization in the AM context, involving data management and manipulation tasks.

To support these conceptual foundations, the authors conducted experiments and tests to gather insights on how BIM and GIS data can be effectively managed according to business needs, current system limitations, resources, and requirements.

3.3 Test and experiments on software applications and tools.

Throughout the design and handover phases, specialized tools are employed to facilitate iterative and extensive data manipulation activities for generating BIM models. The authors sought to explore the applicability of these tools for Asset Management (AM) purposes and conducted tests on two software solutions: Autodesk Revit's Dynamo plug-in and the "Asset Manager" tool in Bentley OpenRail Designer CE Edition. Both tools enable users to carry out batch operations, including property set and properties creation, parameter updates, and more. Dynamo adopts a Visual Programming Language (VPL) with a graphical user interface (GUI) to facilitate script development, although some level of programming familiarity is still necessary. Conversely, the "Asset Manager" tool follows an approach more aligned with traditional AM systems and user experience. It employs pre-structured Excel files, allowing users to batch assign property sets and properties to the necessary entities. This tool expedites the rapid incorporation of especially pertinent data for integration with InRete.2000, such as the "Sede Tecnica" ID and the class code. The tests began with the creation of a BIM model of an actual location using data and documentation provided by RFI, which included a geodatabase (.gbd) containing point clouds, 2D shapefiles of the asset, digital terrain models (DTM), and orthophotos. Furthermore, RFI guidelines and the class database of the “Sede Tecnica” classes were made available. These tasks were conducted in the “BIM model creation” step shown in the overall workflow is summarized in Figure 3. Once the BIM models have been developed, the authors wanted to employ them both with commercial software (i.e., Autodesk Infraworks) and open-source tools (ifcopenshell, IfcJS). In this article, we acknowledge that only the workflow “BIM/GIS viewer POC” is introduced and discussed; however, a comprehensive discussion of the “BIM web-based viewer and AM module” workflow is intentionally omitted because it is still in development and to avoid an excessive length of the article.

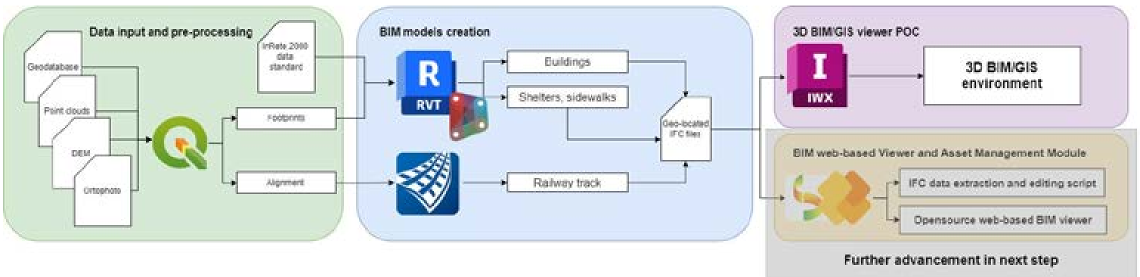

Figure 3 Workflow of the different software and tools tests performed in this study.

Shapefiles provided the asset footprint and alignment, along with coordinates and InRete.2000 data. These data were used to develop the BIM models. Buildings were modeled with Autodesk Revit (2022-2023 version), with simple architectural models linked together to provide an overview idea of a set of contiguous assets. From QGIS, as shown in Figure 4, the “Info Project” pop-up window is shown with the two most important data, namely the ID of the “Sede Tecnica” and the class code of the InRete.2000 data model. To replicate the attributes and values of the data from the shapefile attribute table to the BIM models, several paths can be undertaken after the export of the table in a spreadsheet.

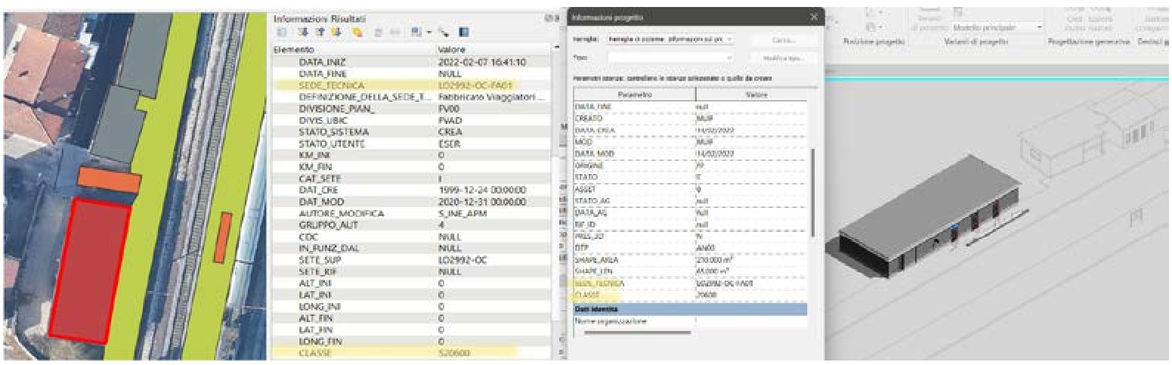

Figure 4 Shapefiles in QGIS (left picture) and derived BIM models (right picture.)

In Figure 4 is also reported a 3D view of the model, with the other developed models attached to check the correctness of geolocation data. Data at “asset-level” has been assigned to the “Info Project” entity in Revit. During the export to IFC files, information about the main SeTes representing the nodes and the edges of the railway network can be associated to the IfcProject or IfcBuilding entity. To handle the large amount of data that should be added to or extracted by BIM elements, batch parameters procedures are an opportunity to save time and reduce errors. Shifting to Bentley OpenrailDesign CE, the same process has been performed for railway tracks using the Asset Manager pre-structured excel files. These two workflows were shown to the interviewees, for feedback collection. Both the aforementioned processes require commercial software, even if an IFC file is used. These kinds of tasks are typically performed by designers (usually not an RFI employee). However, the authors are confident in the idea that companies like RFI may adopt similar tools for the management of data inside their AIM BIM models. In fact, these tools provide semi- or automated procedures for data extraction and manipulation which can ease the link of BIM models with InRete.2000 and MUIF. For this reason, the IfcOpenShell and IfcJS library are also under test to implement sample scripts for extracting, validate and store data in JSON or CSV format for information exchanges with InRete.2000 and MUIF, based on REST API protocols. Compared to commercial software, these libraries allow to develop bespoke script for the extraction and manipulation of data from IFC models. However, this improved flexibility and interoperability requires dedicated team of developers compared to “out of the box” commercial software, and thus companies such as RFI needs to evaluate which alternative best suit their needs and capabilities.

In addition to the criticalities regarding information management and exchanges, interviewees raised an issue regarding the limitations of MUIF for precise measurements and inspections despite its ability to visualize 2D GIS layers, point clouds, and 360° photos. They expressed the need for a more reliable tool, such as BIM models, to facilitate indoor inspections, object data retrieval, and accurate measurements. For this reason, two alternative integration pathways were discussed. The "basic" integration involves BIM models being integrated into MUIF similar to point clouds and 360° photos, connected to the 2D GIS environment via a URL inserted in an attribute field of 2D GIS shapefiles entities. The "basic" integration, therefore, involves a process-level integration where BIM and GIS data are not manipulated or converted into each other's formats. However, according to the interviewees, this integration can already enhance the aforementioned tasks. Conversely, an "advanced" integration would establish a unified environment where 3D BIM and GIS geometries are visualized together. This advanced integration could be achieved through open-source tools like CesiumJS or QGIS, as well as commercial software options like ArcGIS PRO and Autodesk ESRI GEOBIM. For the purpose of this research, Autodesk InfraWorks, as depicted in Figure 5 was selected because it readily provided a proof of concept for a 3D BIM/GIS environment. The interviewees conveyed that such an environment would yield significant benefits to their core business tasks, providing enhanced context visualization, multi-scale dimensioning and data aggregation at larger scales. However, despite recognizing the advantages of the "advanced" approach, the interviewees exhibited a stronger interest in the "basic" integration due to its easier implementation. While the "advanced" approach was seen as a desirable future goal, the interviewees identified complex change management efforts as the main hindrance to its company-wide implementation.

Figure 5 Infraworks 3D BIM/GIS environment for proof of concept.

4. DISCUSSION

Upon the findings of the Focus Group, interviews and experiments, two relevant points of discussion were identified. The first one focuses on the technical aspects of the BIM/GIS integration for infrastructure AM, discussing two alternatives which could be implemented in the short- or mid-term. The second point is about the organizational aspects, which according to the authors should require a deeper investigation in future works.

4.1 Pathways of BIM/GIS integration for AM

For the “Test and experiments” of this study (sub-section 3.3), a limitation is that Semantic Web Technologies have not been tested. This is due to the fact that RFI currently relies on relational databases, and transitioning to more advanced tools like graph databases and ontologies may present a challenging change management effort while a full BIM adoption is still in progress. According to the outcomes of the “Test and experiment” activity, the development of custom scripts and software to link the BIM AIM CDE with existing systems could prove advantageous for AM activities by reducing error-prone manual data management. The interviewees expressed positive feedback regarding several functionalities available within BIM authoring tools, particularly the Visual Programming Language (VPL) features of Dynamo. As a result, the authors suggest that a potential AM-specific BIM solution could incorporate VPL or similar tools as one of the possible modules to enable guided scripting for AM purposes.

Regarding the second research question, it was found out that the answer hinges on the chosen approach and thus it is strongly correlated to the third research questions (i.e., how to integrate BIM and GIS). For these reasons, in this work two approaches are considered, named “basic” and “advanced”, yielding distinct outputs in terms of benefits and hindrances. The "basic" integration primarily involves linking BIM models and shapefile attributes with tailored scripts for data management. This integration allows for converting simple data and geometries from BIM models into the GIS system, such as footprints and project-level information. In the MUIF web-environment, BIM models can be accessed as a separate frame by clicking on the GIS 2D representation. Despite its simplicity, this level of integration already provides benefits for maintenance tasks such as census activities and on-site inspections. For asset management and maintenance tasks, non-geometric data are commonly related to the asset itself and does not require an intensive integration with territorial data. However, efforts and resources must be dedicated to developing solutions for managing non-geometric data and handling sets of properties across multiple systems, using the "SeTe ID" as the matching key. Following an OpenBIM approach, a BIM-viewer inside MUIF web application can be implemented by means of IFCjs or ifcopenshell libraries avoiding intensive rework inside the existing system.

Conversely, the "advanced" integration unlocks the potential for converting conventional 2D spatial analysis into a dynamic 3D realm, seamlessly incorporating attributes like elevations, building stories, BIM components, and more within a comprehensive 3D BIM/GIS environment. The primary advantage of this approach lies in the amalgamation of asset-specific and territorial data within a single interactive environment, enabling querying and management capabilities across diverse assets, such as multiple BIM models of railway bridges. In contrast to the "basic" integration, where each BIM model resides within its individual window frame, the "advanced" approach facilitates asset-specific data analysis on multiple models coherently. Moreover, 3D BIM/GIS visualization contributes to increased awareness of the impact of the asset in the environment compared to its footprint on a 2D GIS map. Thus, the “advanced” approach allows for a comprehensive 3D model of the railway network assets alongside other assets (e.g., from third party sources) and digital terrains. However, its implementation is more complex and costly, especially with open-source approaches, due to the technical pipelines and workflows required to utilize BIM data in a 3D GIS environment. There exists a clear trade-off in benefits between the "basic" and "advanced" integration. While 3D BIM/GIS models enable 3D spatial and data analysis, achieving it demands intensive efforts with open-source solutions or the adoption of commercial software. In perspective of the development of the framework, a “integration layer” should be conceptualized to highlight that the choice of a BIM/GIS integration approach directly influence the “business layer”.

It is also important to consider the recent advancements of the latest version of the IFC schema, i.e., IFC 4.3. Even if crucial for semantic interoperability between BIM-based software, it is worth noting that in the AM context the link with other systems may be driven by specifying an attribute which allows companies to implement its company-level data model or classification systems. In the case study performed with RFI, the “Code of Sede Tecnica” attribute implemented in the BIM model act as a global ID of the asset throughout the other systems such as MUIF and InRete.2000. This approach can ease both the implementation of the “basic” and “advanced” integration, since it enables a certain degree of interoperability even if several elements in the BIM modeles needs to be exported in IFC files as IfcBuildingElementProxy entities.

4.2 BIM/GIS integration insights for framework development

Given the expansive nature of BIM/GIS integration for AM, it is essential to approach it at the organizational level as a systematic, step-by-step process, delineated into "modules" or "key functions". This segmentation allows for the assessment of enabling technologies, prioritization, benefits, challenges, and other pertinent aspects for each module. For instance, one module could pertain to the "BIM/GIS viewer," evaluating its necessity and applications. In this context, the aforementioned "basic" integration would enable swift asset location on GIS, while inspections would be conducted using a BIM-only viewer. On the other hand, assessing how a BIM model of a railway route interacts with train stations necessitates a 3D BIM/GIS viewer, as envisaged in the "advanced" integration. Another illustrative module could be "AM data analysis," aiming to empower BIM/GIS-based business intelligence and data analysis tools. The adoption of this modular approach mandates the formulation of a well-considered change management strategy that aligns with existing information systems, processes, and staff competencies. Without such a strategy, companies might choose counterproductive BIM/GIS integration solutions. While advanced solutions may seem preferable, adopting a modular mindset enables companies to opt for a cost-effective "BIM/GIS viewer" module while concentrating greater resources on other modules. Therefore, concerning the third research question, organizations should strive to associate the benefits of modules with particular tasks, such as utilizing a 3D BIM viewer for asset-wise measurements or employing a 3D BIM/GIS viewer for context-wise measurements. The framework currently in development not only aims to provide a module-based view of the problem, but it is also linked to the primary concerns and needs emerged from the semi-structured interviews and Focus Group outlined in the sub-section 3.2. It's worth noting that both the "basic" and "advanced" does not serve as substitutes for MUIF or InRete.2000. Furthermore, modularity enables changes to be implemented incrementally. For example, if only a BIM-based data exchange for InRete.2000 is required, it can be developed without the need for investment in a BIM/GIS viewer. However, it is important to emphasize that these assumptions hold true if there is a comprehensive understanding of the existing systems employed, as they will inevitably impact the effectiveness and significance of BIM/GIS-based modules and tools in relation to business activities and objectives.

As a future work, the authors aim to embed this concept in the development of the framework, highlighting this "modularity by design" approach for the specific case of RFI as a novel contribution to the current body of knowledge. This approach is intended to provide the framework with a certain degree of generalization, since it is also meant to be a replicable tool for asset owners responsible for other kinds of infrastructures. In the AM phase, BIM is addressed by means of AIM. Since they are considered the backbone of Digital Twins (DT) (Lu et al., 2021), the framework is also intended to be extendable with modules regarding other technologies and tools such as Internet of Things (IoT), Machine Learning (ML) and Virtual/Augmented Reality (VR/AR) (Johansson & Roupé, 2022) which could uplift AM activities. However, these strides necessitate preliminary steps, and BIM/GIS integration is among the most intricate. Compared to previous researches, the ongoing work presented in this article aims to provide a connection point between the advanced proposals found in literature (e.g., semantic web technologies, brand new BIM/GIS systems) and the short- and mid-term needs of organizations involved with AM. Hence, this work addresses the second research question by offering guidance and assessment on implementing changes within existing systems. As a theoretical implication, this research aims to contribute providing two research directions. First, a BIM/GIS integration approach specific for AM should take in consideration the feasibility and the concept of "modularity" and to "innovate with the lowest degree of changes required to the overall existing system architecture". The second research direction is related to the analysis of specific BIM requirements for AM software features and the definition of core skills and needs of a "AM-BIM specialist". Unlike prior phases, the escalating significance of non-geometric data, the pivotal role of open non-proprietary formats, and the dynamic nature of working with AIMs highlight the need for a professional role currently undefined. Furthermore, while BIM authoring tools in earlier phases evolved naturally from preceding tools (e.g., AutoCAD), BIM/GIS-based AIM software poses challenges as it requires integration into existing AM systems. In light of this, the authors recommend investigations into change management for AM-specific BIM/GIS integration, spanning tool prerequisites and professional roles encompassing competencies, core skills, and training.

5. CONCLUSION

The work presented in this paper marks an intermediate stage within an ongoing research endeavour focused on the development of a BIM/GIS integration framework for efficient assets management in the railway context. Starting from this, the framework will be enriched by insights derived from literature, two case studies, and experiments with both open-source and commercial software. Tests involved the creation of simple 3D BIM models from existing data sources, batch data manipulation and BIM/GIS representation alternatives. As a future work, the authors plan to extend the applicability of the framework to complex infrastructures beyond railways. One limitation of this current work is its reliance on the perspective of an Italian case study; thus, a future Swedish case study is being developed to enable a comparison and generalize the framework's applicability. Another limitation lies in the exclusion of widely discussed software like ArcGIS PRO and FME. Instead, Autodesk

Infraworks was selected for the purpose of the proof of concept. Additionally, the company's unfamiliarity with semantic web technologies restricted the inclusion of this technology in the study.

The results of this work are geared towards contributing to two distinct research directions. Firstly, pertaining to the technical facets of BIM/GIS integration for infrastructure asset management, the suggestion is to explore alternatives that can be readily comprehended and implemented by companies. This implies that BIM-based solutions should be approached more as adaptive tools designed to seamlessly integrate with existing GIS and AM systems. This is preferable to introducing disruptive, entirely new systems that would necessitate significant investments and comprehensive system overhauls. The second research direction focuses on organizational aspects. Change management emerges as a pivotal factor in BIM/GIS integration and should be closely aligned with the operational, tactical, and strategic levels of asset management. Several tools and procedures can be tailored from BIM software employed in earlier phases to benefit asset management. However, this adaptation necessitates a profound comprehension of the organization and may warrant the establishment of novel professional roles, such as AM BIM specialists. The final goal of this work is to contribute to the body of knowledge by addressing this multidimensional problem suggesting “modularity” as a key concept for BIM/GIS integration-based AM frameworks. Regarding this, future works in this research will address the complexity of the technical alternatives declined with the capabilities (i.e., resources, staff training, tools etc) of organizations. It is important to note that, without effective change management, companies might encounter counterproductive BIM/GIS integration efforts, which could substantially impede investments intended to enhance the quality and functionality of critical and complex infrastructures, such as railway networks.

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INTEGRATION BETWEEN ENTERPRISE RESOURCE PLANNING AND BUILDING INFORMATION MODELLING

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ABSTRACT: *Enterprise resource planning (ERP) is an integrated business management system aimed at monitoring and maximizing resources and efficiency; on the other hand, Building Information Modelling (BIM) represents a broad series of approaches to design, based on the development of virtual models that cover the building's whole lifecycle. The integration of ERP systems within the Architecture, Engineering and Construction industry, while promising, has yet to reach the same results that its use has achieved in other fields. Although BIM and ERP are traditionally systems employed in different disciplines, they both deal with data integration and customization, and are designed to reconcile varied and scattered information. A mutual incorporation could allow for a more comprehensive understanding of the project starting from the initial phases, while also granting a more streamlined construction process and a reduction in errors and complications later on. The aim of this paper is to identify the possible connections between the two systems examining a case study, starting from an analysis of the current state of the art regarding this implementation, and by evaluating both the existing limits and the future possibilities of this implementation, for both small and medium enterprises (SMEs) and the industry at large.*

KEYWORDS: *Enterprise Resource Planning (ERP), Building Information Modelling (BIM), Small Medium Enterprises (SMEs), AEC, Construction, Data integration*

1. MANAGEMENT INFORMATION SYSTEM AND ENTERPRISE RESOURCE PLANNING

1.1 Brief history of ERP

Enterprise Resource Planning is a type of business information system meant to manage and monitor all the resources within an organization. Introduced in the 60s within the manufacturing industry as Material Requirement Planning (MRP) (Lee, Arif, & Halpin, 2002), the system mainly focused on the storage and allocation of materials. In 1975 IMB then developed the Manufacturing Management and Account System (MMAS), now considered the true precursor to ERP (Jacobs, 2007): the system was aimed at creating ledger postings, job costings and related forecasting updates based on the inventory status and order transactions, while also generating orders using a standard Bill Of Material (BOM).

The consequent technological growth enabled, during the 80s, the development of the Manufacturing Resource Planning (MRP II) system, which allowed the integration of functions related to human resources and marketing, as well as the management of all financial and accounting information (Kumar, & Van Hillegersberg, 2000). The ability to manage and update orders, inventory and financial transactions in a single system, allowed the companies to replace and centralize multiple typically stand-alone systems with a single software, resulting in easier communication between different areas and the automatization of data sharing.

However, the term ERP wasn't coined until 1990 by Gartner (Katuu, S. 2020), in order to describe a new generation of unified systems that could manage different departments within the same company, and that were based on the standardization and integration of processes within a single, shared database. This new type of management software also dealt with back-office data, financial transaction, marketing, and all the information related to all the different production stages, from planning and procurement to transportation and delivery. A rapidly growing business, ERP sales crossed the $10 billion mark in 1998 (Shi, & Halpin, 2003), with companies like J.D. Edward, Oracle, PeopleSoft, Baan and SAP surpassing IBM and positioning themselves as leaders in the ERP market. A critical factor in the success and spread of the software was also the so called Millennial Bug, or Y2K Problem, which was thought to cause global electronic damage due to how programs used to format year dates; in order to prevent possible informatic problems at the switch of the millennium, many companies took advantage of the

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)

Paola Federici, Daniela Julea, Sara Comai, Kavita Raj, Silvia Mastrolembo Ventura, Giuseppe Rigamonti, Giorgio Paolo Maria Vassena, Angelo Luigi Camillo Ciribini, *Integration Between Enterprise Resource Planning and Building Information Modelling,* pp. 443-453, DOI 10.36253/979-12-215-0289-3.43

necessity to update their own software and implemented ERP systems, cementing the software's consolidation in the industry.

Despite a promising start and initial accounts reporting a Return On Investment ranging from 30 to 300% within a year after installation (Shi, & Halpin, 2003), many failures were also accounted: the main problems were mostly related to the initial costs of purchase and installation - which, at the time, varied from $2 million to $130 million (Ross, 1999), and the time needed for full implementation, as well as the likelihood of a performance dip during the stabilization phase of the software, which was expected to typically lasts for four to 12 months. By 2002 all main ERP distributors faced a significant stock plummet: Baan had fallen off by then, and J.D. Edwards and PeopleSoft opted for a merger between the two companies, since there was very little overlap between what the two software offered and the joint venture was thought to, in this way, manage to exceed SAP and Oracle (Jacobs, 2007); nevertheless, Oracle itself took over the merger after a few days with an hostile takeover, leaving itself and SAP as the main distributors.

In the meantime, a new system was being developed: Extended ERP, or ERP II, not only allowed for real time access to information and immediate data sharing between members of the company, but also had managed to integrate two other software, Supply Chain Management (SCM) and Customer Relationship Manager (CRM), which could manage interactions with suppliers regarding procurement and transportation, while also handling clients' data (Al-Amin, Hossain, Islam, & Biwas, 2023). The advent of the digital era, paired with the difficulty for Small and Medium Enterprises (SMEs) to bear the software's implementation and managing costs, resulted in the development of Cloud-based ERP systems: in this case, the system runs on the provider's cloud platform as opposed to an on-premises hardware that needs to be handled by a IT team employed by the company. Traditional ERP software, developed for an easier but less flexible management than what the market requires today, have been proven to be insufficient in handling the complex internal processes required within an enterprise, as they are not able to grant the same streamlined integration that a cloud system can offer.

Many possibilities are viable today considering the advancements of technologies within the 4.0 Industry, one of which could be the development of ERP Mobile platforms, accessible from smartphones through internet connection, and that could allow for easier and instant access to information and more customization possibilities. The introduction of AI and Machine Learning could also quicken processes, thanks to the prediction of inventory status and the atomization of repetitive processes, as well as error predictability; the integration of IoT solutions, such as smart sensors, could, too, facilitate the monitoring of materials and equipment within the supply chain.

1.2 ERP within the construction industry

1.2.1 State of the art

ERP systems are currently used by construction companies in order to:

- Improve customer response time;
- Improve relationship with suppliers while also strengthening the supply chain all together;
- Increase organizing flexibility;
- Reduce time related to decision making processes, as well as the competition times and related costs.

Considering the great level of customization that this kind of management system can offer, it might seem impossible to define a standard ERP software for an industry like the AEC (Architectural, Engineering and Construction) one, which is incredibly fragmented and characterized by different areas of work, each one of which has its own particular needs, usually related to the specific project currently being worked on. As Helo and Szekely (2005) mention, many are, in fact, the benefits that an ERP system can provide, such as the possibility to immediately develop a Master Production Schedule which allows sales orders and forecasts, the creation of purchasing orders for suppliers and production orders for plants, the constant update of inventory statuses updated depending on procurement and delivery status, and tracking of financial records of both the customers' orders and the company's internal status regarding payroll and suppliers payments. Integrating an ERP system inside the company can help manage all this information within one single centralized software, allowing for a more streamlined sharing of data, which can prevent errors or duplicated records during the various stages. This implies a sort of standardization of processes that, while it can result in more transparency and rapidity during the processes and, all around, a general improvement of performance, clashes with the nature of the construction industry.

Multiple attempts have been made in order to push the industry towards the same levels of efficiency that this kind of implementation brought to other branches, while failing to get the same results (Gavali, & Halder, 2020): the outcomes achieved by sectors that rely on standardized mass production such as the production and manufacturing industry – industries ERP systems where developed by and for (Kumar, & Van Hillegersberg, 2000) – seem to be unrealistic for construction companies, which work instead on a project by project basis and where every case is characterized by specific needs related to not only the requests of the client, but also are dependent on the different and multiple teams working on the project itself, which vary often and might end up working together for the first time. As Yang et al (2007) noted, the Construction Managements packages offered by commercial ERPs cannot provide a once-and-for all model for all industries, much less for construction firms, especially considering how the level of digitalization and use of IT solutions within the industry is still very low and far from the rationalized and mechanical nature of other sectors.

Though, as of today, this type of technology cannot manage a reality so fragmented and unpredictable nor the increment of complexity within projects, the flexibility required by 4.0 Industry, and the recent development of technological advancements, require the establishment of a new type of interoperability between systems and a new way of designing and planning.

1.2.2 Construction Enterprise Resource Planning

According to Augenbroe (2006), an ERP system can be divided in two interfaces, one related to the project and one to the financial aspects: the development of a stable and clear link between the two – granted by a common access to the financial data, project data and customer data - is essential in order to allow a more streamlined planning and decisional process. In the construction industry in particular, the system should be project-oriented, since the project itself is the cornerstone of the financial activities: in order to ensure the handover of the construction within the established timeframe and costs, an efficient organization of the ERP system is needed.

As explained by Dudgikar et al (2012), the software allows the company to manage its own resources, split into:

- Manpower, meaning the definition and planning of the workforce, as well as identifying the teams and the skills required, especially if the work requires the introduction of subcontractors and their crews within the project;
- Materials, which groups all processes aimed at materials planning, programming, and their purchase, inventory control, materials transportation and handling on site;
- Machines, which handles, for example, the acquisition and management of all the equipment, and the identification of the tasks to be undertaken by said mechanical equipment;
- Money, including financial forecasts, project budget and cost control measures.

The company, then, needs to coordinate not only internal resources (workforce, equipment, inventory …) which can be handled directly, but also various external influences (suppliers' transactions, subcontractor relationships, market situation …) from which it depends on. Whoever is tasked with the decision-making process has then to manage a vast quantity of information that belongs to different areas, and that must also be properly recorded and shared.

Shi & Halpin (2003) developed the so called Construction Enterprise Resource Planning (CERP) system, an internet-based framework that develops in three tiers: one related to the User Interface, related to clients' management and data, one related to the Management Servers, which provides administration and the link between the other two levels, and one related to Applications, which includes the database of the system and all the project and materials information. This type of system can offer immediate access to all the data, granting better performance and quickness within the decisional stage; by being a cloud-based system, this system also supports a more transparent and collaborative process, as all information is stored within the system itself and is readily available to everyone, and can be traced to the person tasked with the transaction or the decision made.

The main obstacles of these applications can still be ascribed to the costs and time required for implementation and development of the systems, and the lack of software and modules that can handle the complexity of the processes typical of the construction industry. While the aim of these systems is to standardize and automate the workflow, so that every individual can access and use them easily, the landscape of this industry is still too fragmented and requires a level of specificity often incompatible with these goals.

1.3 ERP-BIM Integration

A potential integration between ERP software and BIM models could be one of the viable solutions aimed at facilitating the implementation of ERP system in construction companies. The status of this integration is, nowadays, still at the embryonal stage: the first pursuits focused on the attempt to connect the manufacturing data to the information related to the construction processes by exploiting 2D CAD files, but failed to define an efficient information-centric approach that could establish a proper integrated work frame (Holzer, 2014).

Within the multiple causes of these undeveloped integrations between the two systems, the main one can be traced to the slowness of the AEC industry in implementing solution related to the digital management of the designing and planning stages: the creation of digital and parametric virtual BIM models is still too underdeveloped in many companies, and rarely this way of modelling also takes into consideration the procurement or the construction process. Particularly, SMEs are especially the ones struggling with the development of these systems, mostly because of the lack of properly developed IT systems, which would allow for a more digitized process. As Ghosh et al (2011) point out, the time and costs implementation and management of these software is, once again, the main cause, as well as the lack of investments in proper staff training. Considering also the typical traditional and conservative outlook still very present within the industry, and the very high rates of change of technology solutions (Andresen et al, 2002), it’s easy to imagine why these kinds of processes are rarely pursued by SMEs.

In light of the potential developing a common platform or a direct integration between ERP and BIM systems, one of the fundamental traits must be full transparency between all the involved parts, and constant and clear communication. Considering the typology and the volume of data and information that would be managed in this scenario, this kind of communication and integration requires a properly defined planning process starting from the initial phases: basically, a preliminary planning stage should take place well before the designing process itself, so that complications and unexpected events can be prevented or properly handled beforehand.

This sort of reengineering process is described by Kahn (2021), who proposes a total reshuffling of the typical designing and planning processes, resulting in a shift of the stress of workload to the initial stages, and a better distribution of efforts all-around. In this case, the Operation Stage, which includes 3D Coordination, design review and site work, is given the most emphasis, allowing for a better organization between the teams, a consequent reduction of designing and construction times. A transparent and well-developed coordination since the initial stages is therefore needed and the solution can be the connection between the ERP system and the BIM model.

2. CASE STUDY

For the purpose of achieving an integration between the ERP system and the BIM model, a real case study was analyzed. The following examination also takes into consideration the management system used by the construction company, in this case SAP, that was in charge of the construction of a building that covers an area of 1400 square meters. As part of this analysis, a first attempt was made to link the ERP software and the information model; ideally, the goal would be to directly integrate the two system so that changes within the model (in terms of 3D objects volumes and quantities, for example) could be automatically recorded by the ERP software, resulting in the update and correction of data and information related to material orders and scheduling.

2.1 Project content within the management and control software

In the initial stages of construction planning, a comprehensive preliminary Bill Of Quantities (BOQ) was compiled, which took into consideration the cost and pricing of materials, the need for equipment and workforce, taking into account not only the market average prices, but also personal agreements settled between the company and the suppliers or subcontractors. The structure used to define the BOQ during these initial exchanges between the construction company and the clients was therefore replicated in the ERP system, in order to consider every material, item and construction task, and their placement within the construction timeframe.

In order to translate and develop the construction timetable within the Project Builder of the software, a dedicated project profile was meticulously created. This project profile has been subdivided into discrete "Work Breakdown

Structure Elements," serving as a crucial classification system to effectively categorize the essential tasks for the comprehensive project plan. By using a top-down approach, the project structure branches out into multiple "networks", which represent the succession of activities that define the construction processes and that are characterized by start-to-end relationships and various interdependencies related to the time schedule of the task itself. These element profiles are used to plan, analyze and monitor time and resources during the whole construction timeframe: in this way, all the items present in the Bill Of Quantities are actually translated into the management system, each one representing a particular task on site and its related information.

These elements, that essentially represent every material used during the construction project and, in this way, its relative activity on site, are sorted with the following data:

- Milestones, which are required to proceed with payments;
- Information regarding the production centers related to the supply chain;
- Standard duration and minimum duration for each task (in terms of days); ideally, this kind of information should be the result of data obtained from the production center, however, it is often necessary to proceed with manual data entry of the durations, according to the schedule defined by the timetable;
- Deadlines: the start/end relationships between activities are determined in this section, as well as which task has the priority over the others within the construction process, and any time buffers that might need to be taken into account due to possible delays;
- Data relating to materials' orders, in the case of outsourced work. This section collects data referred to the identification of the supplier, its prices, cost items and planned delivery times, as well as data related to purchase requisitions managed by the accounting department.

2.2 ERP-BIM link

In order to develop a connection between the BIM model e the ERP system, only a small part of the whole project was taken into consideration. The work mainly concerned two categories of materials: concrete elements (exclusively focusing on the main structures, meaning the pillars and the load bearing walls on the main floor, the foundation slab, and roof) and drywall components. These elements were specifically chosen for a few reasons: firstly, these materials were enriched with the biggest volume of information - especially for the concrete, and therefore were considered ideal examples to test the potential transfer of data between the two system. Secondly, these are very different and partially antipode materials: on one hand, once arrived on site, the concrete cannot be stored, and has to be poured and used within a certain time frame; additionally, the concrete samples must go through a meticulous round of controls and checks, whose resulting documents can be collected and archived in the ERP system by connecting them to their relative object inside the project network. On the other hand, drywall elements, used here for vertical and slanted elements and for the false ceilings both, can be stored and stocked within the perimeter of the construction site for a long period of time, and have to undergo a less strict process of control and verification.

Considering the nature and the purpose of the ERP system, the time aspect and the possibility to whether to store or not the materials are especially crucial: delays in previous works, changes regarding the delivery dates of materials, or eventual changes in the project can influence the progress and continuation of the whole construction phase. Therefore, the possibility to track these changes directly and quickly, whether from variations in the BIM model or notification from the site, is essential in order to coordinate the work time schedule, the procurement and the delivery of materials and resources.

In order to then develop a proper connection, upon gathering all the pertinent data related to the tasks and materials taken into consideration for this analysis, links have been developed in order to establish a direct correlation between the ERP system and the information model. This connection was accomplished through the exportation of URL links related to the materials in each phase: each material is, in fact, within the project system, enriched with all the information collected from the accounting team (e.g. purchase orders, delivery dates, and all information previously mentioned), the project team (e.g. quantities, locations, construction phase…) and from site personnel (lab results and any type of documents collected on site). Once extracted (Fig 2.), the hyperlink can be sent by e-mail. Furthermore, the mail can be sent along with eventual notes or attachments from the operator, to other professionals who may need it (Fig. 3).

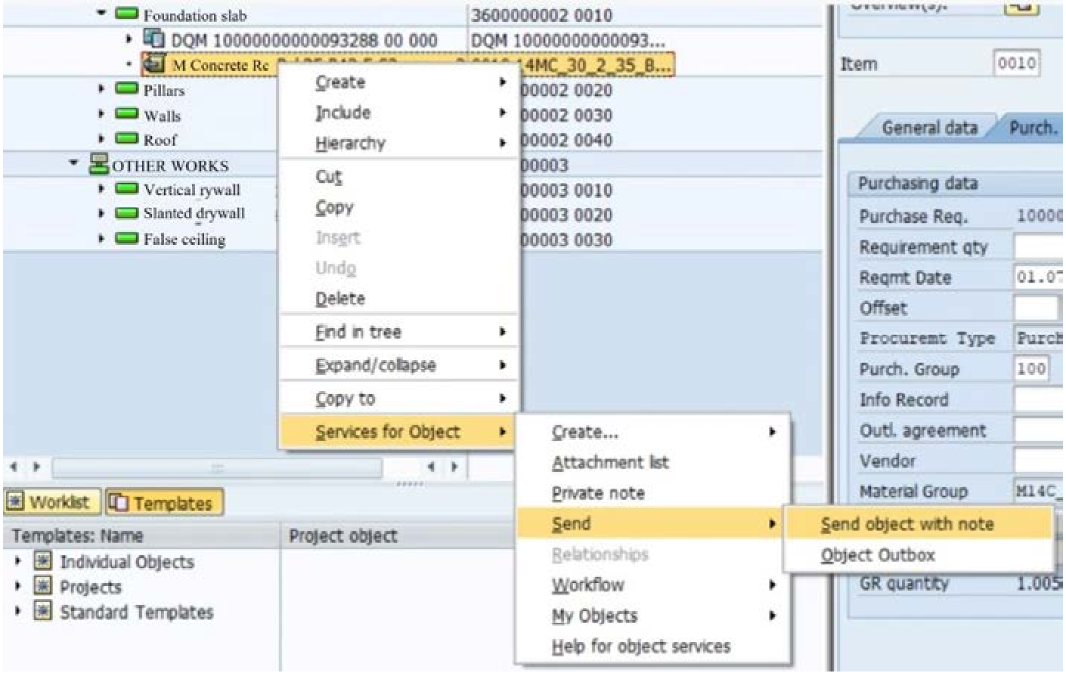

Figure 1. Procedure used to extract URL links related to the material; in this case, the concrete used for the foundation slab.

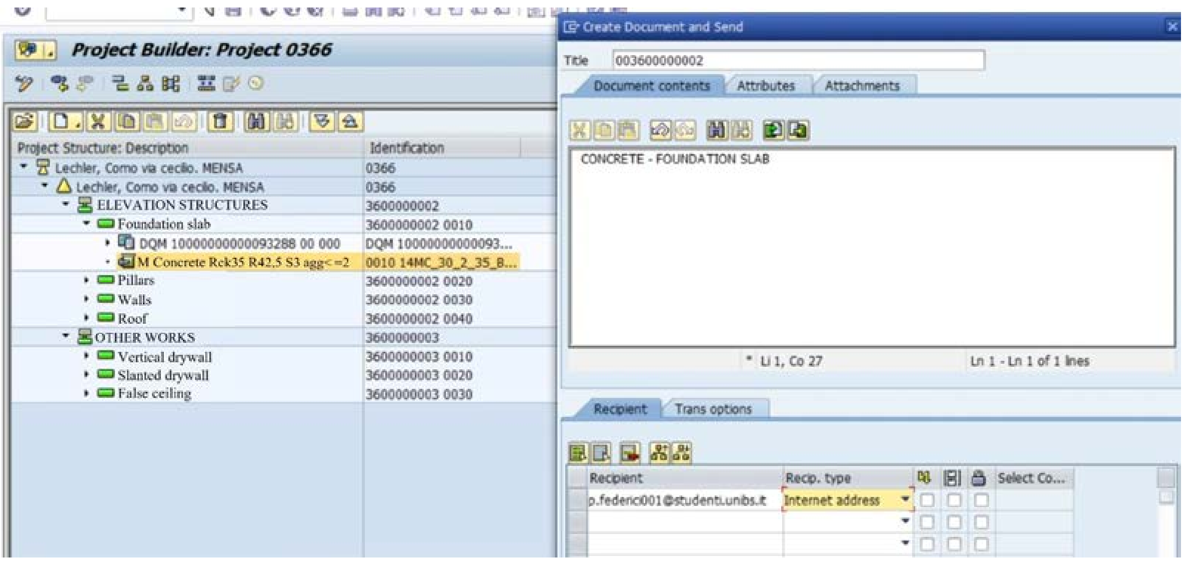

Figure 2. Creation of the URL link, related to the material, that can be sent via e-mail along with eventual notes and attachments.

The URL link provides direct access to the interface of the material, which collects and groups all the information related to the material itself and its construction activity on site, as previously mentioned. The hyperlink was then incorporated into the 3D object properties that belong to every object in the information model in the modelling software; by clicking it, the operator can directly access the ERP interface related to the material taken into account. In order for this connection to be operable, the personnel needs to, of course, have to access to the ERP system and the project at hand, and be familiar with the ERP interface and use. A basic run down of the system then would be needed for all the professionals within the work frame, in order to understand and make use of the connection.

The possibility to export a link that can directly bind an object inside the model to its material in the ERP system enables the association of the material with multiple objects at the same time, as they refer to a specific item rather than a task, effectively increasing the information and data strictly related to the object within the BIM model. For example, rather than extracting a single different link for each pillar built, which would consist realistically into a different activity each on site, a singular link to the specific type of concrete used was extracted: the link then brings up the related item in the ERP system, showcasing prices, deadline, schedules, orders and all the data related to that specific activity. In this way, an effective direct link was created between the BIM model and the ERP.

On the other hand, it is, again, necessary to point out that the access is limited to approved personnel since they are the only ones having the authority and responsibility to develop the project in the ERP system. Moreover, at stage of this case study, the linking system is not only manual, but also static, since it needs to be constantly updated.

3. AUGMENTED REALITY TOOLS AND PROCUREMENT

Another way to establish a link between the 3D BIM model and the ERP, concerns the use of the augmented reality (AR) tools. Through the AR technology it is in fact possible to overlap the BIM model containing the digital information, and the physical space of the construction site; thus, the data contained in the property set of the BIM model will be transposed to the matching objects in real life.

Thanks to this superimposition, AR is conventionally primarily used for project monitoring and control, but it can also be employed to implement the logistical aspects related to the procurement of materials and to their storage within the construction site. Through the use of an AR mobile app, by selecting each 3D BIM object, it is possible to notify its status in real life in terms of procurement information. In this way, every member of the construction and designer team gets to know in real time if a specific object is identified, ordered, delivered, checked, or installed, and the corresponding information can be recorded in the ERP system (Wang and Love, 2012). The planning of the supply and procurement of materials can be easily updated, allowing a more effective planning of subsequent orders. Similarly, it is possible to track the availability of materials by precisely defining the requirement for the consecutive period, guaranteeing an on-time supply approach.

3.1 Definition of status notification for the case study

Each status notification groups a potentially wide amount of information, therefore their selection based upon predefined criteria is fundamental. In the specific case study - in addition to the above-mentioned advisory of identification, order, delivery, check and installation - the information considered most significant to form this type of report (Fig. 4) are:

- Object of the notification and location in the construction site;
- Figure in charge: in order to fill out this field, one or more companies responsible for the procedure of supply and installation of the object must be selected;
- Expected date for delivery and installation of the object attending to the construction schedule;
- Properties of the BIM object: this field, unlike the others, cannot be filled in by the individual completing the status notification. The properties of the object are inherited from the BIM model and automatically entered in the field to avoid errors and to speed up the signaling procedure.

Considering the purpose of the object status notification, the most significant property concerns the Work Breakdown Structure (WBS) code which uniquely identifies the selected objects. These alphanumeric codes are also present in the ERP network and allow the operator to identify the corresponding purchase order and to update it by registering a delay.

Once all the fields have been completed, the final report will be visible on a web platform to which only specific members of the team have access to. The operator who is in charge of updating the orders on the ERP software will be notified via e-mail and will consequently look for the matching WBS code in the ERP network and act consequently.

As for now, the transfer of this kind of information from the construction site to the ERP takes place manually, due to the lack of interoperability between the software involved in the procedure; nevertheless, it is easy to imagine that the automatization of the process is the next achievement that needs to be accomplished in the future developments of the technologies and tools involved (AR, 3D BIM, 4D BIM-ERP).

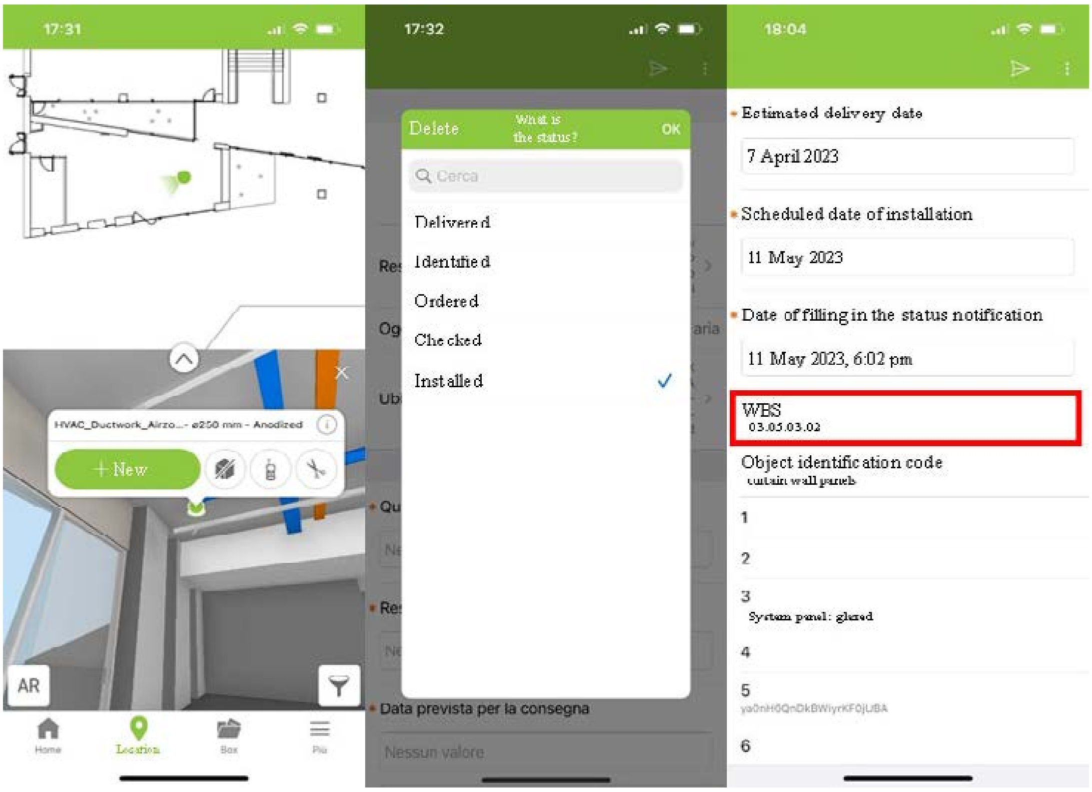

Figure 3. From left to right: (a) Selection of the object the completion of the Status Notification is referred to. (b) Multiple-choice responses to indicate the object's status. (c) Properties of the BIM object, automatically collected from the model: the WBS code is highlighted.

Ultimately, the two types of connections between the BIM model and the ERP system established operate in accordance with the diagram presented in fig.4 and necessitate a continuous update of information following the recording of new data obtained through the surveying of the construction site.

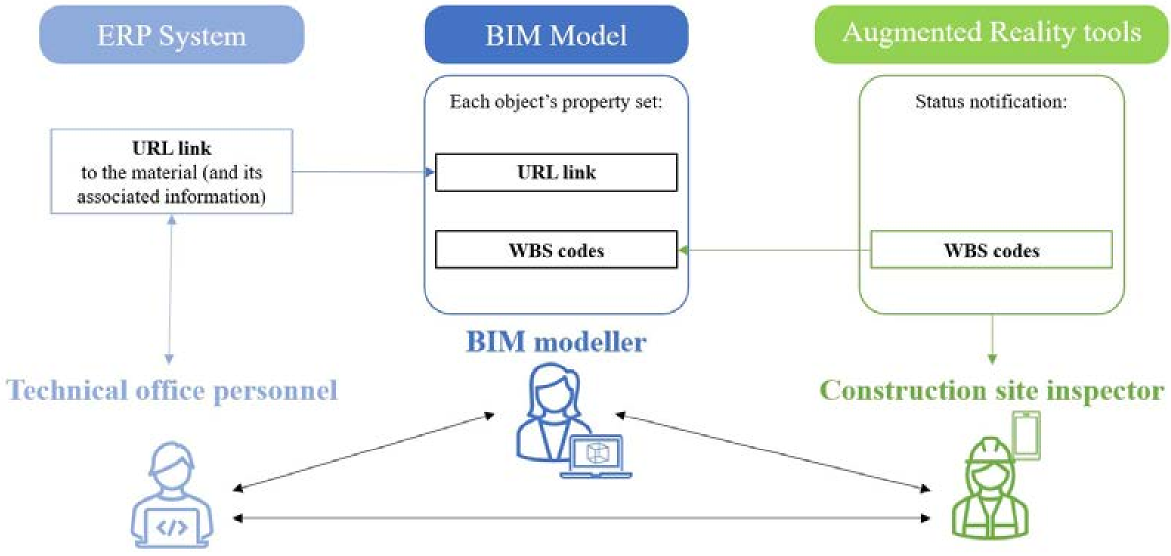

Figure 4. Schematic drawing of the procedure for establishing the ERP-BIM connection. An URL link is extracted from the ERP system and incorporated within the properties of objects in the BIM model, alongside WBS identification codes. Utilizing augmented reality tools, the Construction Site Inspector generates status notifications, which subsequently inform the BIM modelers and the Technical Office personnel of the current progress of the ongoing work. Both the BIM model and the information contained in the ERP system will be updated, and the flow will potentially start over again.

4. CONCLUSIONS

Through the process described, it was possible to develop a connection between the ERP system and the BIM model, both by the development of a hyperlink between the material stored in the management system and its own 3D object, and by the establishment of status notifications sent directly from the construction site to the company's system.

While effectively linking the two systems, the connection created remains, as mentioned, accessible only to those who have access to the company's management system, as the software access credentials are required to be able to view the system interface. Furthermore, the hypothetical idea of connecting the material in the ERP system to the 3D object belonging to the information model currently constitutes a manual and non-automated task, resulting in an exceedingly laborious process, especially considering the number of objects modeled and the materials used. Moreover, the link appears to be static and unidirectional: any change made to the BIM model, such as alterations in volume quantities or material types, are not directly perceived and recorded by the ERP system, and every modification has to be arranged manually. Similarly, item entries updates within the ERP system do not automatically update within the link, which would need to be exported again and consequently replaced in the 3D object properties.

As mentioned, it is still a very preliminary and underdeveloped connection, still manual for the most part, and far from the potential goal of streamlined automatization between the two systems.

To achieve a higher level of integration, the development of a potential plug-in bridging the gap between the modeling software and ERP software would be necessary: since these two systems were designed for different purposes and objectives, mostly due to the different industries they were developed for and by, establishing a direct connection between the two programs would entail the involvement of the respective software distribution companies. Their cooperation and a great amount of resources, both in terms of time and investments, would be required to generate a bidirectional linkage between the systems.

In the eventuality of such a development, it would become crucial to take into consideration the high level of variability that characterizes not only construction projects, but also the coordination and management of these projects by construction firms. The perspective of a full-scale ERP-BIM integration would imply the standardization of the designing, planning and managing processes within the AEC industry, so that the transaction developed within the software can be distributed and used universally. This would result in an adjustment of the management procedures between the companies, further facilitating collaboration and communication.

5. ACKNOWLEDGEMENT

This research was partially funded by the Italian government through the PRIN2017 project entitled “Distributed Digital Collaboration Framework for Small and Medium-Sized Engineering and Construction Enterprises”.

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DEVELOPMENT OF AN AUTOMATED WORKFLOW IN THE FIELD OF FIRE PREVENTION USING BUILDING INFORMATION MODELING

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ABSTRACT: *The research focuses on an approach for the development of an automated workflow in the field of fire prevention for the validation of BIM models regarding "Subjected Activities" (according to Italian law - Presidential Decree 151/2011), with reference to the contents of the Horizontal Technical Regulation of the Fire Prevention Code. In fact, since 2019, the Italian Fire Department, through the Fire Digital Check project, is seeking to digitize the Fire Prevention Code in order to allow professionals to integrate their BIM models with the objectives required by the fire regulations. The workflow proposed involves three distinct processes, integrating them within a single workflow: study of the technical regulations and transposition into the digital environment using proven methods such as RASE, Tx3 and TIO, information modelling of a case study and implementation of validation algorithms using Solibri software. One of the main points of the proposed process is to use an open and interoperable format such as that offered by the IFC schema for the information exchange between the different software involved.*

KEYWORDS: *fire prevention, BIM, validation, code checking, digitization*

1. INTRODUCTION

With the Industry 4.0 approach, the construction sector has been involved in the development of systematic digitization processes (Daniotti et al., 2022) and its progressive transformation into a data-driven production sector appears to be irreversibly (Mêda et al., 2021). Furthermore, in recent years the introduction of information management with Building Information Modeling (BIM) tools and methodologies in public supply, service and works contracts has highlighted the need to define structured and planned data flows and information exchange between the various phases of the construction process. This text is intended as an in-depth study on the subject of digitization within the technical-administrative processes concerning public administrations with a thematic focus on fire safety in Italy. In particular, it describes and presents an application of a workflow aimed at checking BIM models to be submitted to algorithms for automatic validation and verification of the contents of the Fire Prevention Code D.M. 03-08-2015.

The following software was selected for the application of the workflow, which met the requirements that emerged in terms of flexibility in model creation, data export and control: Autodesk Revit, as BIM authoring software, and Solibrì Model Checker, as BIM model checking software. The proposed structure, however, want to be more general, in fact it does not require the use of specific software and exchange formats, and for its implementation reference was made to proven methodologies for the translation of normative code such as TIO, Tx3, RASE. The exchange of data between proprietary software was also carried out using the IFC (Industry Foundation Classes) format, which is an open standard, developed by buildingSMART, capable of describing the ontology of the building and the different specialisations related to a generic building process, through the use of entities, properties and relationships. In addition, the use of such data schema has become mandatory for any BIM services in the public sector in Italy.

The application of the workflow presented in this paper refers to "subjected activities" to the controls of the the National Fire and Rescue Service in accordance with D.P.R. 151/2011, without a Vertical Technical Rule, within the project evaluation procedure. This is limited to the automatic validation and verification of the contents of the Fire Prevention Code D.M. 03-08-2015 at *Section S.1 - Reaction to fire*. The starting point and main reference of this work was the Fire Digital Check project, born from the will of the Department of Fire, Public Rescue and Civil Defence to undertake the necessary digitisation process of the fire prevention procedures provided by D.P.R. 151/2011.

2. STATE OF ART

BIM modelling of new or existing buildings guarantees a homogeneous database capable of transmitting

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Vincenzo Donato, Andrea Bongini, Marco Sparacino, *Development of an Automated Workflow in the Field of Fire Prevention Using Building Information Modeling,* pp. 454-465, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.44

information not only regarding the geometric component of an object but also its informative and documentary characterisation. The model assumes in this context not only the meaning of a geometric representation of building components but rather becomes a database where all the information produced in the different phases of the building process can be collected (C. M. Eastman, 2011). This methodology can be applied for new buildings as well as for existing buildings (Volk et al., 2014), and in particular much research is being developed on HBIM field (Murphy et al., 2013) for the digitisation of historical heritage (Biagini et al., 2022). The digitisation of all this assets must, however, be followed at the same time by a digitisation also of the national and international regulations so that it becomes possible to apply automated or semi-automated methodologies for the verification of these rules and the issuing of authorisations in the design phases of an asset. The concepts of clash detection and code checking, defined in the UNI 11337 standard as 'analysis of possible geometric interferences between objects, models and drawings', and 'information inconsistencies of objects', respectively, become important in this context. The automation of these checks with different tools during the design phases (C. Eastman et al., 2009) has led to many experiments over the years in different areas around the construction process, such as the verification of health and safety requirements in the design of the site layout (Getuli et al., 2017). The Singapore government has been a forerunner in this discipline through the CORENET e-PlanCheck project, developed by a collaboration between the Ministry of National Development and the Construction and Real Estate Network, which proposed the automatic checking of BIM models in the open IFC format. In general, code checking can be set up as a multi-domain framework based on a set of parametric rules (Solihin & Eastman, 2016; Zhang et al., 2013) that can be generated on the basis of quantitative specifications derived from a text.

The objective of this study is to understand which parts of a specific regulation are most easily digitised and how to translate these into verifiable entities or parameters within a BIM model through a combination of different methods (Solihin & Eastman, 2015). A reproducible workflow for the digitisation of a regulation using proven methods, such as TIO, Tx3, RASE, is then proposed for analysis (Hjelseth & Nisbet, 2011).

RASE (*Requirement - Applies - Select - Exception*), is a methodology aimed at identifying key points within the regulatory text. The latter are selected, classified and organised schematically with the aim of simplifying the elaboration of rules that can be implemented through programming languages. These operations are generally carried out by highlighting the text using coloured mark-ups that correspond to precise types of content within it. The portions of text that can be defined as necessary or requested requirements are highlighted In blue (*requirements*), the portions that define the scope of applicability of the requests or necessary requirements are highlighted in green (*applies),* the portions of text that contain the object or reference to the request or necessary prerequisite are highlighted), in red (*select*), and finally the portions of text that refer to an exception or that otherwise restrict the scope of applicability of the requested requirements are highlighted in yellow (*exception*).

Tx3 (*Transcribe - Transform - Transfer*), is a method aimed at expressing the degree of translatability of regulatory text into digital language. This is a very important assessment to make, since this translation process is not always advantageous and it may happen that the result obtained does not justify the time taken to achieve it. Basically, the method involves the classification of standards into three different categories: *transcribe*, i.e. those parts of normative texts that can be easily translated into digital language, usually prescriptive norms fall into this category; *transform*, parts of normative texts that can be rewritten while retaining their implementation purpose, but which often require the introduction of constraints such as qualitatively defined benchmarks but from which it is still possible to translate the requirements quantitatively; *transfer*, instructions that cannot be implemented due to the imprecise way in which they are expressed within the reference text, such as benchmarks that are not defined quantitatively but only qualitatively.

TIO (*Test Indicator Objectives*), has the objective of bridging the gap between qualitative and quantitative requirements in such a way as to be able to increase the degree of digitisation for the former, thus allowing them to be incorporated into the process. This is a very important step as the most difficult requirements to translate are often qualitative ones, because they cannot always be correlated to quantitative parameters or measurable quantities.

In order to verify the applicability of these procedures, it was decided to take as a reference the Fire Prevention Code, for which a discussion table on its possible digitisation has already been started in Italy at the beginning of 2019 as part of the BIM-FDC (Fire Digital Check) project, aimed at automating the validation of Fire Prevention projects drawn up with the code, limited to compliant solutions. A combination of the above methods was then used to digitise the regulatory text, limited to section S.1 of the code.

The TIO method, aimed at translating the requirements expressed in qualitative terms, and at identifying parameters that allow their verification and control, allowed the results of the risk analysis to be parameterised, and to correlate parameters such as R_{Vita}, R_{Beni}, $R_{Ambiente}$ that characterise an activity (or compartment) to specific requirements. The Tx3 method, on the other hand, was used to verify only the compliant solutions foreseen by the Fire Prevention Code. Given the high specificity of the alternative solutions, which do not generally have a prescriptive character, these must eventually be treated in a specific way for each case study and are not suitable for verification within a general automatic validation methodology. Finally, by means of the RASE methodology, the object to which the regulatory prescriptions of Section S.1 refer is identified: in this specific case we refer to the scope of the subjected activities, defined by the code in section G. In addition, a distinction has been made between the areas that constitute "escape routes" of the activity (or compartment) and areas that constitute "other spaces" of the activity, since different levels of performance are generally required of these, depending on the *Life Risk* attributed to the activity (or compartment).

3. METHODOLOGY

The workflow presented within this paper is based on the application of the BIM methodology in the field of fire risk management and the validation of the related regulatory features. Specifically, the objective is the automatic validation of BIM models concerning subjected activities (according to D.P.R. 151/2011), with reference to the contents of the Horizontal Technical Regulation of the Fire Prevention Code. Three distinct areas can therefore be found in the process: technical regulations, BIM modelling and validation algorithms. Each of these areas must relate to the others, and for each of these relationships objectives and criteria for their achievement must be defined.

Technical Standard - BIM Modelling. Technical regulations contribute substantially to determining level of development of BIM models. Operationally, therefore, it determines what is to be modelled.

Technical Standard - Validation Algorithms. Technical standard provides the basic parameters, criteria and logic for the implementation of validation algorithms.

BIM Modelling - Validation Algorithms. The data structures of BIM models must be organised according to predefined criteria, so that the necessary information is available for the application of validation algorithms. At this juncture, a standard must be defined for the databases on which the logic of the algorithms can be developed.

3.1 Preliminary study of legislation and information exchange

Annex I of the Fire Prevention Code 'Technical Regulations for Fire Prevention' consists of the following Sections: G (Generalities), S (Fire Strategy), V (Vertical Technical Rules) and M (Methods). From the study of the relative contents of the Sections, with reference to the scope of application and the objectives set, it was possible to define a workflow for the digitisation of the Code as shown in the figure (fig. 1).

The following methodology is based on the following principles:

1 - validation is performed on BIM models inherent to a specific subject activity (pursuant to D.P.R. 151/2011);

2 - risk analysis, the definition of design goals and safety objectives, and risk assessment, are steps that must necessarily precede the entire workflow from the creation of the BIM model to its validation. These steps need a specific assessment by a fire safety professional. From here, we arrive at the quantitative definition of the R_{Vita}, R_{Beni}, $R_{Ambiente}$ parameters for each compartment of the subject activity, which represent input data for the project;

3 - on the basis of the R_{Vita}, R_{Beni}, $R_{Ambiente}$ parameters, the minimum required performance levels are identified within the chapters of section S of the Fire Prevention Code, and for these, through the digitisation of the regulatory text, the parameters that determine compliance with the relative solutions are identified;

4 - when creating the BIM model inherent to the subject activity, geometric and alphanumeric data are defined by the fire protection professional responsible for the project;

5 - the achievement of these performance levels is verified through the application of the compliant solutions set out in the code, which, in general, are prescriptive in nature. Verification must take place by means of automatic validation procedures, using a library of algorithms specifically created for this purpose, which is applicable to each subject activity without a Vertical Technical Rule. This library of algorithms must also be scalable and reusable for more complex projects;

6 - the workflow does not provide for the application of alternative solutions to achieve the minimum performance levels.

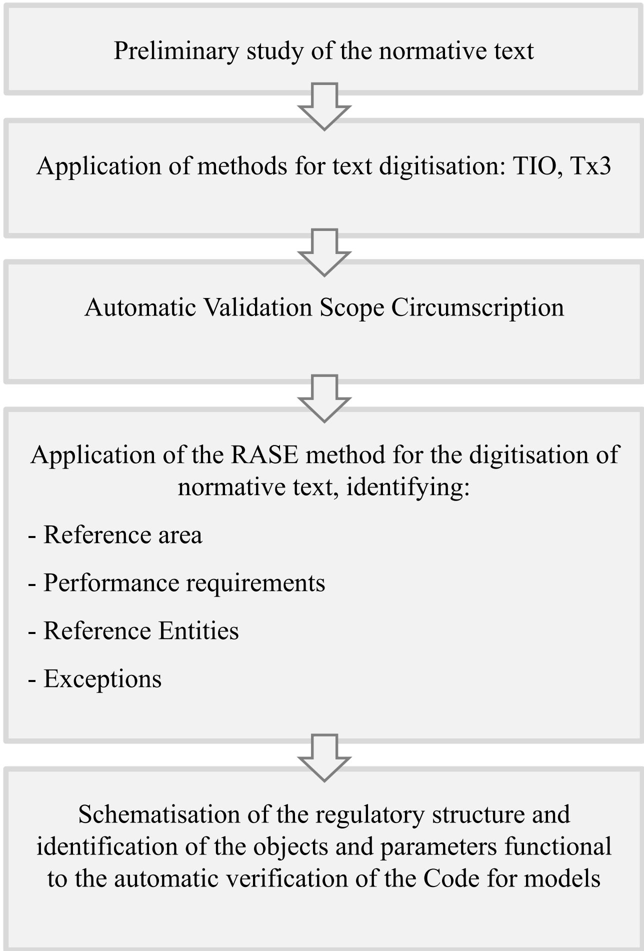

Fig. 1: Workflow for digital translation and parameterisation of normative text.

Based on these assumptions, three main work packages were then set up: the analysis of the regulatory text and its digitisation, the BIM modelling of the activity subject to regulatory control, and the application of algorithms for the validation of the BIM model. The first phase involved the definition of information requirements, in the form of alphanumeric parameters and geometric characteristics, which were to be included in the model and subsequently subjected to verification. The second phase involved the modelling of the considered activity, including not only the geometry, but also the design parameters that need to be. The last phase, on the other hand, led to the application of validation algorithms of the BIM model with reference to the contents of the Fire Prevention Code in order to verify the achievement of the minimum performance levels required for a generic subject activity.

Whereas the objectives and the actors involved in this information exchange process, each with its own tools and software, it is necessary to answer to two needs: to provide BIM authoring and code checking software capable of managing open and interoperable exchange formats, and to define a standard for the data structures to be exchanged, so that the information content within the model can be correctly analysed by the automatic validation algorithms used by the Fire and Rescue Service. Autodesk Revit BIM authoring software was then used to create the geometric model and assign the required parameters, then its information content was exported in IFC format. Once exported in IFC, it is possible to open this model within any model checker software, in our case the Solibri Model Checker software (Office version) was used, and to perform the validation operations on several levels.

The image below (fig. 2) shows the schematisation of which entities were involved in the verification algorithms. In particular, it shows the hierarchy of the spaces within the entire activity subject to inspection and where the areas for which specific performance levels are to be verified are located.

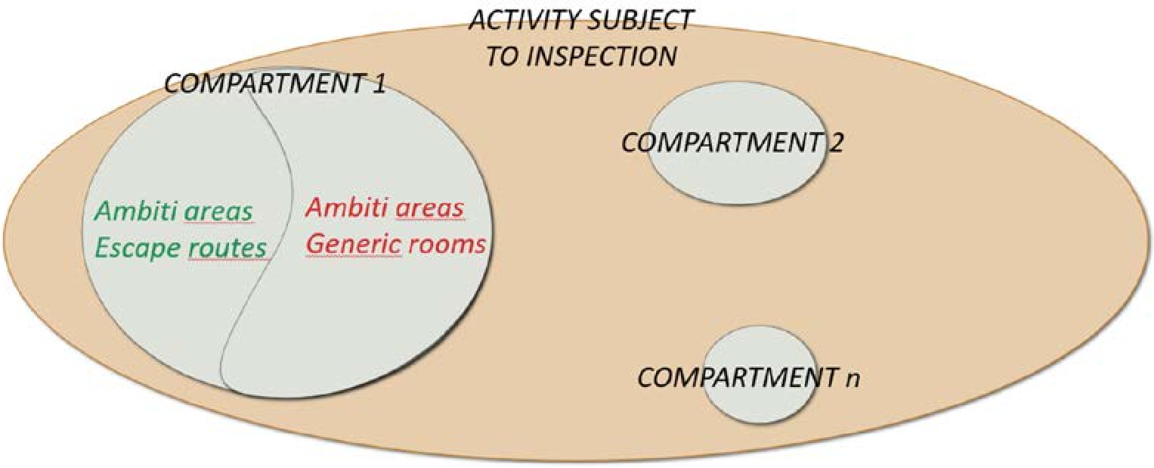

Fig. 2: Outline of the functional structure for digitising the code - Section S.1.

To achieve the required performance levels, some of the objects in the areas will have to have certain fire characteristics. The diagram below (fig. 3) shows what was modelled in the workflow application.

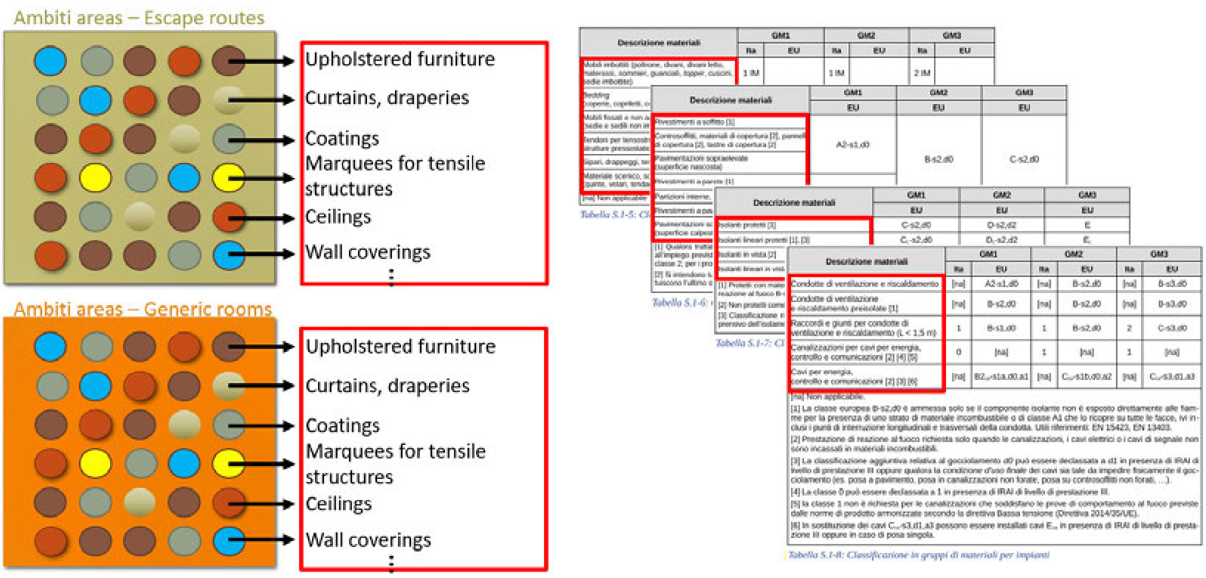

Fig. 3: Identification of the entities subject to verification within the schematic structure for code digitisation purposes.

3.2 P_set definition

The process of rule interpretation and digitisation of the normative reference text necessarily entails the definition of specific parameters that will subsequently be used in the verification process. Furthermore, in order to efficiently organise the data structure contained in the model, it is necessary for parameters to be grouped into specific Property Sets. This will make it easier to retrieve the necessary data to be analysed at a later stage. As part of the digitisation of section S.1 on the achievement of *Fire Reaction Performance Levels*, with reference to the normative structure outlined in the previous chapter, the elements to be modelled and the parameters to be assigned to them are defined.

Two entities were modelled within the BIM authoring software: activity scope and material. The tables below show the parameters associated with these two entities.

Table 1: List of parameters associated with the Ambiti areas of activity.

Property name	Property type	Description
NomeCompartimento	IfcLabel	Its value makes it possible to define to which compartment a given domain belongs, so that all domains belonging to a given compartment can be filtered in the validation processes
RVita	IfcLabel	Its value corresponds to the Life Risk determined during the risk assessment for a given compartment. By assigning the Life-Risk of the relevant compartment to each area, the performance level required for the Fire Reaction characteristics can be easily linked to it.
ViaDiEsodo	IfcBoolean	Its value makes it possible to determine the type of scope, as this contributes to determining the required minimum performance levels.

Table 2: List of parameters associated with materials.

Property name	Property type	Description
ClassificatoReazioneAlFuoco	IfcBoolean	Its value is used to determine whether an object representing the Material entity within the model falls within those listed in Tables S.1-5, S.1-6, S.1-7, S.1-8.
GruppoReazioneAlFuoco	IfcLabel	Its value, assigned with reference to the provisions of Ministerial Decree 26/6/1984 and Ministerial Decree 10/3/2005 by the fire protection designer, frames the fire reaction characteristics of a material, which, as can be seen in the normative text, are closely related to the minimum performance levels indicated by the law.

4. CASE STUDY

Modelling inside the BIM authoring software Autodesk Revit, within the scope of application of this methodology, is carried out for a simplified case study characterised by the structure shown in the table.

Table 3: Pilot model structure.

ACTIVITY SUBJECT TO FIRE BRIGADE INSPECTIONS			
COMPARTMENT 01		COMPARTMENT 02	
R_{vita} = D1 – R_{beni} = 1 Rambiente = NC		R_{vita} = B2 – R_{beni} = 1 Rambiente = NC	
Ambito 01	Escape Route	Ambito 02	Escape Route
		Ambito 03	Generic Room

Each *Ambito* (area of activity) within the Revit software was modelled as space, then exported as IfcSpace class within the IFC scheme. Regarding the modelling of the construction and furnishing elements that are covered in the tables of the Fire Prevention Code (S.1-5, S.1-6, S.1-7, S.1-8), and subject to verification in the validation process, the objects in the table below were modelled.

Table 4: Identification of the entities subject to verification within the pilot model structure.

[Compartment 01]	**Ambito 01**	n.3 Upholstered furniture [Category: Furniture]
		n.1 Floor covering [Category: Floor]
		n.1 Suspended ceiling [Category: Ceiling]
		n.1 Protected insulation [Category: Wall]
	Ambito 02	n.3 Upholstered furniture [Category: Furniture]
		n.1 Floor covering [Category: Floor]]

		n.1 Suspended ceiling [Category: Ceiling]
[Compartment 02]		n.1 Protected insulation [Category: Wall]
		n.3 Upholstered furniture [Category: Furniture]
	Ambito 03	n.1 Floor covering [Category: Floor]]
		n.1 Suspended ceiling [Category: Ceiling]
		n.1 Protected insulation [Category: Wall]

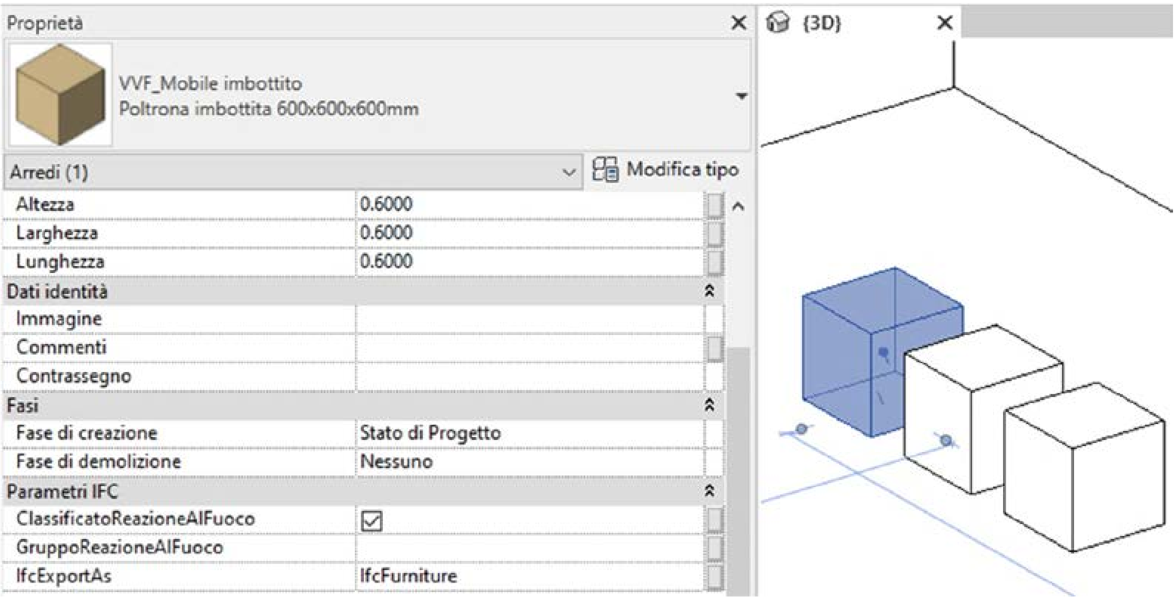

Fig. 4: Functional parameterisation for automatic validation of entities within the model.

To reach the level of information contained in the model and to implement the subsequent automatic validation process, it is necessary to enter the parameters foreseen during the digitisation of the normative text by assigning them to the modelled entities. These parameters were created as shared parameters, organising them in an external text file and therefore reusable in other models. Once the parameters had been assigned to the categories of the modelled objects, the data subject to verification were entered (fig. 4). The data assigned to the parameter GruppoReazioneAlFuoco did not in all cases reflect the requirements of the Code for achieving the minimum performance level required of the area belonging to a particular Compartment. This was an intentional error in order to show any issues that may result from the analysis.

The next step involved exporting the model created in the BIM authoring software in the open IFC format. The operation was carried out by first checking the settings of Revit's IfcExporter, analysing that the correct IFC classes corresponded to the different entity categories present in the model. Should it prove useful to further specify the IFC export class for a single instance, it is possible to exploit the shared parameters collected in the specially provided PSet_IFC_Exporter Property Set. As far as the export of parameters within the IFC format is concerned, these were organised in specific custom P_sets, through the structuring of a special file in .txt format subsequently called up in the Revit software export settings. Once the model was exported in the IFC schema, it was possible to open the latter within the model checking software. The image below shows how the imported model, displayed in the three-dimensional view, is represented by an organised data structure characterised by the hierarchy defined during the model creation phase (fig. 5).

At this point, within the model checking software we proceed to set up the groups of validation algorithms for the BIM model. Referring to what emerged from the study of the structure of the Fire Prevention Code, for the complete realisation of a library of verification algorithms, a library of Rulesets organised as shown in the table 5 is envisaged.

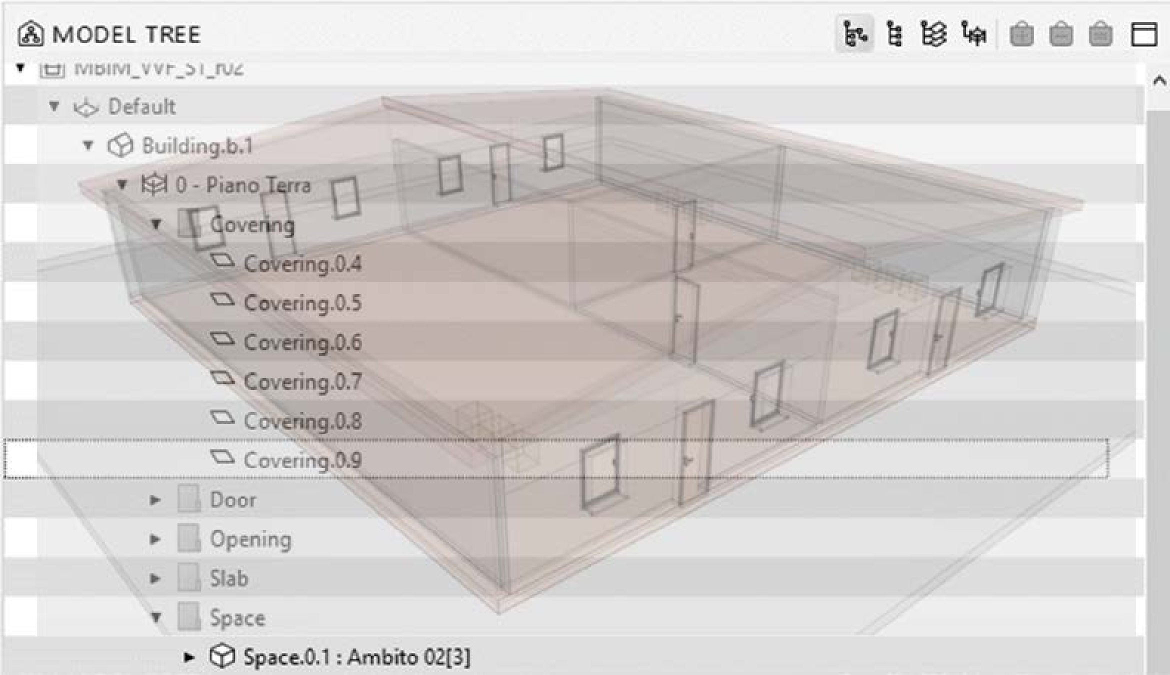

Fig. 5: Representation of the BIM model within the automatic validation software.

Table 5: General ruleset structure for the automatic validation of the fire prevention code

RULESETS	
Ruleset Name	Function
VVF_S.1_ReazioneAlFuoco	Verification of conforming solutions
VVF_S.2_ResistenzaAlFuoco	Verification of conforming solutions
VVF_S.3_Compartimentazione	Verification of conforming solutions
VVF_S.4_Esodo	Verification of conforming solutions
VVF_S.5_GSA	Verification of conforming solutions
VVF_S.6_ControlloIncendio	Verification of conforming solutions
VVF_S.7_RivelazioneAllarme	Verification of conforming solutions
VVF_S.8_ControlloFumiCalore	Verification of conforming solutions
VVF_S.9_OperativitàAntincendio	Verification of conforming solutions
VVF_S.10_SicurezzaImpiantiTecnologiciServizio	Verification of conforming solutions
VVF_G _AnalisiDelRischio	Data compilation check
VVF_Altro	Data compilation check

Each of the rulesets listed above will contain specific validation algorithms for the BIM model built with reference to the Code conforming solutions set out in the ten Chapters of Section S of the Fire Strategy. Two further rulesets are also foreseen: VVF_G _AnalisiDelRischio, dedicated to the control of the correct compilation of the parameters relative to the risk analysis, and VVF_Altro, dedicated to the control of parameters not directly referable to the contents of sections G and S of the regulations, but necessary to define the more complex validation algorithms.

Accordingly, for the purpose of validating the contents of Section S.1 of the Code, the structuring of the internal subgroups of the Ruleset VVF_S.1_ReazioneAlFuoco is given.

Table 6: Ruleset structure for the verification of reaction to fire performance for a compartment characterised by a generic risk profile.

RULESET - VVF_S.1_ReazioneAlFuoco	
Subgroups of validation algorithms	Function
VVF_S.1_ReazioneAlFuoco_Controllo	Verification of correct compilation of validation parameters
VVF_S.1_ReazioneAlFuoco_A1	Verification of Conforming Solutions by Activity or Compartment R_{vita} A1
VVF_S.1_ReazioneAlFuoco_A2	Verification of Conforming Solutions by Activity or Compartment R_{vita} A2
VVF_S.1_ReazioneAlFuoco_A3	Verification of Conforming Solutions by Activity or Compartment R_{vita} A3
VVF_S.1_ReazioneAlFuoco_A4	Verification of Conforming Solutions by Activity or Compartment R_{vita} A4
VVF_S.1_ReazioneAlFuoco_B1	Verification of Conforming Solutions by Activity or Compartment R_{vita} B1
VVF_S.1_ReazioneAlFuoco_B2	Verification of Conforming Solutions by Activity or Compartment R_{vita} B2
VVF_S.1_ReazioneAlFuoco_B3	Verification of Conforming Solutions by Activity or Compartment R_{vita} B3
VVF_S.1_ReazioneAlFuoco_C1	Verification of Conforming Solutions by Activity or Compartment R_{vita} C1
VVF_S.1_ReazioneAlFuoco_C2	Verification of Conforming Solutions by Activity or Compartment R_{vita} C2
VVF_S.1_ReazioneAlFuoco_C3	Verification of Conforming Solutions by Activity or Compartment R_{vita} C3
VVF_S.1_ReazioneAlFuoco_Ci1	Verification of Conforming Solutions by Activity or Compartment R_{vita} Ci1
VVF_S.1_ReazioneAlFuoco_Ci2	Verification of Conforming Solutions by Activity or Compartment R_{vita} Ci2
VVF_S.1_ReazioneAlFuoco_Ci3	Verification of Conforming Solutions by Activity or Compartment R_{vita} Ci3
VVF_S.1_ReazioneAlFuoco_Cii1	Verification of Conforming Solutions by Activity or Compartment R_{vita} Cii1
VVF_S.1_ReazioneAlFuoco_Cii2	Verification of Conforming Solutions by Activity or Compartment R_{vita} Cii2
VVF_S.1_ReazioneAlFuoco_Cii3	Verification of Conforming Solutions by Activity or Compartment R_{vita} Cii3
VVF_S.1_ReazioneAlFuoco_Ciii1	Verification of Conforming Solutions by Activity or Compartment R_{vita} Ciii1
VVF_S.1_ReazioneAlFuoco_Ciii2	Verification of Conforming Solutions by Activity or Compartment R_{vita} Ciii2
VVF_S.1_ReazioneAlFuoco_Ciii3	Verification of Conforming Solutions by Activity or Compartment R_{vita} Ciii3
VVF_S.1_ReazioneAlFuoco_D1	Verification of Conforming Solutions by Activity or Compartment R_{vita} D1
VVF_S.1_ReazioneAlFuoco_D2	Verification of Conforming Solutions by Activity or Compartment R_{vita} D2
VVF_S.1_ReazioneAlFuoco_E1	Verification of Conforming Solutions by Activity or Compartment R_{vita} E1
VVF_S.1_ReazioneAlFuoco_E2	Verification of Conforming Solutions by Activity or Compartment R_{vita} E2
VVF_S.1_ReazioneAlFuoco_E3	Verification of Conforming Solutions by Activity or Compartment R_{vita} E3

As can be seen from the list above, net of the group of rules necessary to control the parameters strictly related to the verification for section S.1, within the Ruleset VVF_S.1_ReazioneAlFuoco there are subgroups of validation algorithms which refer to the specific R_{Vita} attributed to each compartment of the activity, defined in the risk assessment phase. Each subgroup of the ruleset VVF_S.1_ReactionAlFuoco will be the container of validation algorithms necessary to filter the objects to be verified and which in general belong to different types of areas. It may be noted that this type of organisation of the structure for the verification algorithms allows the application of the Ruleset VVF_S.1_ReactionAlFuoco to a BIM model of any activity, even a complex one, and made up of compartments to which different risk assessment parameters are attributed.

It should be noted that the verification algorithms were created from the library contained in the Solibri Model Checker software, which provides a very extensive archive of basic rules, with which even complex validation algorithms can be created. We take the validation algorithms contained in the Ruleset VVF_S.1_ReazioneAlFuoco as an example, highlighting the following subgroups: VVF_S.1_ReazioneAlFuoco_Controllo and

VVF_S.1_ReactionAlFuoco_B2.

The subgroup VVF_S.1_ReazioneAlFuoco_Controllo (fig. 6) provides two control algorithms that verify the presence of the parameters and the correct input of the relative values for the purposes of subsequent Code checks. The first check verifies that all the elements requiring a Fire Reaction classification, and therefore referable to Tables S.1-5 S.1-6 S.1-7 S.1-8 contained in Section S.1 of the Fire Prevention Code, have a plausible value assigned [GM0, GM1, GM2, GM3, GM4] to the GroupFireReaction parameter. The second check verifies the presence of the parameters NomeCompartimento, Rvita, ViaDiEsodo and their compilation with plausible values.

▼ VVF_S.1_ReazioneAlFuoco_Controllo			
§ Controllo 01_DefinizioneParametro_GruppoReazioneAlFuoco	SOL/203/2.4		
§ Controllo 02_DefinizioneParametriAmbitiAttivià	SOL/203/2.4		

Fig. 6: Structure of the control ruleset for the correct compilation of parameters

The subgroup VVF_S.1_ReazioneAlFuoco_B2 (fig. 7) has been divided into two further subgroups whose function is to check the two types of Ambiti areas identified by the Code in Section S.1, namely Vie d'Esodo [VE] and Altri locali [AL]. The rule Ambiti Vie d'esodo_Rvita=B2 has the purpose of filtering all the entities within the model which must comply with Fire Reaction requirements, and which belong, specifically, to Activity Ambiti areas which are Exit Routes and which belong to compartments to which an Rvita=B2 has been attributed during the risk assessment phase. The Fire Reaction characteristics of all objects belonging to these areas will be specifically verified by the following algorithms. The image below shows by way of example one of the verification algorithms which hierarchically follow the rule Ambiti Vie d'esodo_Rvita=B2.

▼ VVF_S.1_ReazioneAlFuoco_B2			
▼ VVF_S.1_B2_VE			
▼ § Ambiti Vie d'esodo_Rvita=B2	SOL/1/5.0		
§ GruppoReazioneAlFuoco_Arredi	SOL/9/3.1		
§ GruppoReazioneAlFuoco_Pavimenti	SOL/9/3.1		
§ GruppoReazioneAlFuoco_Controsoffitti	SOL/9/3.1		
§ GruppoReazioneAlFuoco_Isolanti	SOL/9/3.1		

Fig. 7: Ruleset structure for the identification and verification of performance for the reaction to fire of compartments.

In particular, the tab below refers to the rule GruppoReazioneAlFuoco_Arredi (fig. 8). This takes into account all the elements filtered by the previous algorithm classified as Furniture, for which specific reaction-to-fire characteristics are specified.

Component	Property	Allowed Value
Furniture	PSet_VVF_ReazioneAlFuoco.GruppoReazioneAlFuoco	GM2
Furniture	PSet_VVF_ReazioneAlFuoco.GruppoReazioneAlFuoco	GM1
Furniture	PSet_VVF_ReazioneAlFuoco.GruppoReazioneAlFuoco	GM0

Fig. 8: Definition of possible values for the parameters under verification.

The possible values of the property GruppoReazioneAlFuoco, in this specific case described, are GM2, GM1, GM0. The operation of the remaining rules underlying the rule Ambiti d'esodo_Rvita=B2 is entirely similar and should be defined for each of the materials defined in Tables 5 S.1-6 S.1-7 S.1-8 contained in Section S.1 of the Fire Prevention Code.

Two types of errors found during Code Checking are given as examples:

- Failure to compile the parameters (algorithm for checking the formal correctness of the information model). For some instances, the GruppoReazioneAlFuoco parameter is not filled in, although the objects they represent must necessarily respect precise reaction to fire characteristics to reach the minimum performance level required by the Standard.

- Reaction to fire of materials not suitable for the Rvita value of the compartment (algorithm for checking the technical correctness of the information model). Some instances do not have suitable fire reaction characteristics with respect to the area and compartment in which they are located. The value assigned to the parameter

GruppoReazioneAlFuoco, which are not among those covered by the validation algorithm.

At the end of the validation procedure, the Solibri Model Checking software can generate a report of the issues that emerged during the analysis phase that can be exported in various formats, including the open BCF format, allowing further possibilities for the development of the data flow considered in the methodology presented.

5. CONCLUSION

In the methodology just shown it was possible to observe how automated verification procedures can be implemented for the verification of the Fire Prevention Code, at least regarding the compartment of prescriptive measures given by the conforming solutions reported in the different sections of the RTO of the fire prevention strategy. Although the work presented focuses only on the contents of section S.1, given the RTO's structure and potential, as well as the flexible interoperability between Revit and Solibri software, there appears to be ample scope for the development of Code Checking of the other sections.

In any case, it is necessary to emphasise the importance of developing a standard for BIM modelling, and in particular for the structure of IFC models that, in view of the digitalisation of fire prevention procedures, will have to undergo automatic validation by the Technical Office of the Fire Service. In fact, the same organizaton will implement the code checking phase and it will define the data structure of the IFC model that can then be linked to its set of automatic validation algorithms. Validation algorithms are an information verification tool that needs databases structured according to a declared standard to function properly.

Regarding the necessary characteristics of the BIM authoring software useful for the application of the workflow described in this text, a high degree of flexibility in the export of data in IFC format is considered of fundamental importance, which means having both the possibility of creating user-defined P_sets and the possibility of assigning user-defined properties to the objects in the model. These features will allow the creation of the data structure in IFC format, as required by the validator.

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DATA-DRIVEN CONSTRUCTION AND OPERATING COST DECISION SUPPORT THROUGH TECHNO-ECONOMIC ANALYSIS: RESIDENTIAL CASE STUDY

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ABSTRACT: *Construction and operating costs of residential buildings are important. Because, it can help designers, builders, owners, and renters make informed decisions about where and what to buy or rent. One of the most significant operating costs of residences is energy cost. More specifically, heating, ventilation, and air conditioning account for as much as 35% of the overall energy consumption of buildings in the world. Thus, the problem that this research paper addresses is the decision trade-off of construction costs vs. operating costs. Therefore, this paper aims to perform a techno-economic analysis of exterior residential wall-type alternatives in a warm-humid climate. The research followed a quantitative methodology using a virtual case study with multi-objective analysis. The results of this study show the significant importance of the building's infiltration on the operational savings and the return on investment (ROI) of the different types of exterior residential walls. and emphasizes the importance of a holistic approach to energy conservation regulations. The novelty of this study is the emphasis on the importance of infiltration in pre-construction decision-making. The broader impact of this result is that the International Energy Conservation Code (IECC) and similar standards could be revised to reduce energy consumption and reduce greenhouse gas emissions produced during energy generation.*

KEYWORDS: *Residential, Building Performance, Construction Cost Estimating, Insulation, Infiltration, Return on Investment, Decision Support.*

1. INTRODUCTION/OVERVIEW

Buildings are a major consumer of energy, accounting for approximately 40% of all energy demands for many countries (Farhanieh & Sattari, 2006; Ogulata et al., 2002; Vine & Kazakevicius, 1999). Likewise in the U.S., the building sector accounts for about 40% of all primary energy use, and 76% of electricity use, and is responsible for the significant associated greenhouse gas (GHG) emissions. The major areas of energy consumption in buildings are heating, ventilation, and air conditioning (HVAC) which account for approximately 35% of total building energy. (Department of Energy, 2015)

Various elements affect the energy consumption of buildings. The most important element is the thermal envelope which includes all building components separating conditioned spaces from unconditioned spaces or outside ambient conditions and through which heat is transferred (IECC, 2015). The thermal envelope assembly can have a positive or a detrimental impact on the overall building performance and therefore on the HVAC energy consumption. Although the insulative properties of exterior walls and windows are commonly regulated, with a minimum R-value or maximum U-value, other parameters are not normally considered. A higher insulative value of a wall is not always advantageous, and can also increase the heating or cooling loads, in some cases, despite complying with the legislative requirements for each location (D'Agostino et al., 2019). Another significant parameter that could hurt the performance of buildings is infiltration. Infiltration is airflow into and out of buildings through unintentional leakage in the thermal envelope due to pressure differences induced by wind, indoor-outdoor temperature differences, and the operation of ventilation and other building systems (Persily et al., 2019.). Air infiltration has a significant influence on the energy performance of buildings and can result in excessive energy demand to maintain adequate indoor comfort levels (Ji et al., 2017; Persily et al., 2019.).

The problem that this research paper addresses is the effect that different exterior wall assemblies can have on the operating cost of a building accounting for both the insulative properties and the infiltration level of the building. Furthermore, this study also addresses the initial construction costs to provide insight into the economic viability of these construction updates. The effect of the exterior wall assembly on the building's energy use is a complex issue that depends on many parameters including climate, building use, building design, and materiality (Kaynakli, 2012). Improving the thermal performance of the building envelope can remarkably enhance the whole building's energy efficiency (Abanda & Byers, 2016; Huang et al., 2020). There are various ways of improving the building envelope. As previously mentioned, thermal insulation is one of the most valuable tools in achieving energy conservation in buildings (Ghrab-Morcos, 2005; Kaynakli, 2012; Wang et al., 2007). Furthermore, air infiltration

Referee List (DOI: 10.36253/fup_referee_list)
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Panos Karaiskos, Tulio Sulbaran, *Data-Driven Construction and Operating Cost Decision Support Through Techno-Economic Analysis: Residential Case Study,* pp. 466-476, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.45

improvements can potentially lead to HVAC energy savings on the order of 26% (Tian et al., 2019). The objective of this paper is a techno-economic analysis of an exterior residential wall in a warm-humid climate. The analysis focuses on the effects of the insulative properties of the exterior wall (R-value) and the infiltration rate on the HVAC energy consumption. Furthermore, this study includes a cost estimation analysis for the initial construction costs associated with these assemblies, to quantify the economic feasibility of these proposed construction updates.

2. METHODOLOGY

2.1 Overview of the methodology used

A quantitative research methodology was used in this project using a virtual case study. The virtual case study consisted of a residential building with different wall types and infiltration levels. Each of the wall systems was modeled and the construction cost as well as the energy consumption/operating were determined. This was achieved in three stages: 1- Data Collection, 2- Energy Performance Modeling, and 3- Results Analysis as shown in Figure 1.

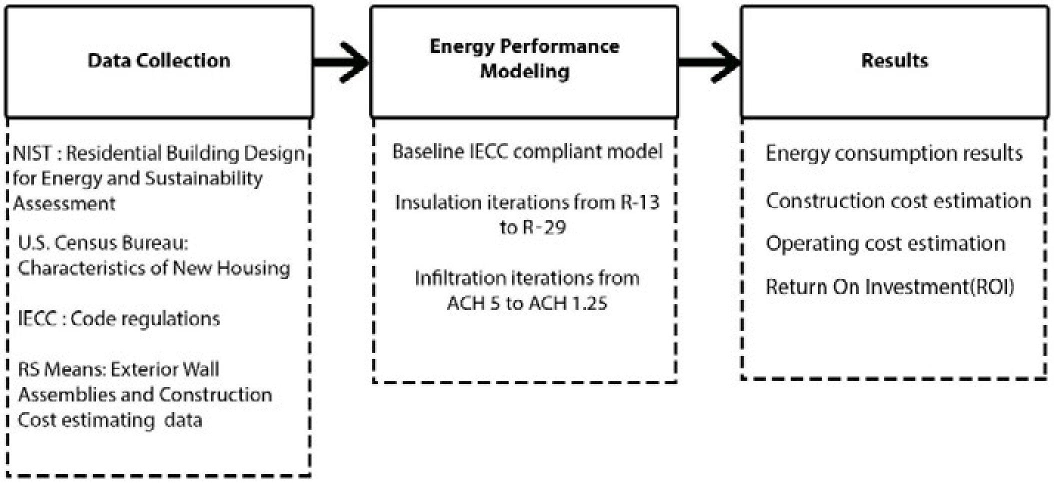

Figure 1: Methodology Diagram

2.2 Data collection process

The data collection was done from multiple sources to design and model the residential building that accurately represented the energy consumption standard and building code in the case study area.

<u>NIST:</u> The general building characteristics were based on the "Prototype Residential Building Design for Energy and Sustainability Assessment" which was published by the National Institute of Standards and Technology (NIST) (Kneifel, 2012).

<u>U.S. Census Bureau:</u> The exterior wall framing type appropriate for this study was selected based on the U.S. Census Bureau's database on residential buildings (*U.S. Census Bureau*, n.d.). As can be seen in Figure 2, for many years wood-frame construction has been the predominant type of exterior wall framing for all residential construction in the U.S. The latest available data shows that out of the 970 thousand new single-family houses built in 2021, 875 thousand were built with a wood-frame method which translates to approximately 90%. For that reason, this study focused on wood-frame-type exterior wall assemblies. Furthermore, because of the nature of wood-frame type wall assemblies, compared to mass-wall type assemblies, this study did not include thermal inertia as a parameter of the performance analysis study.

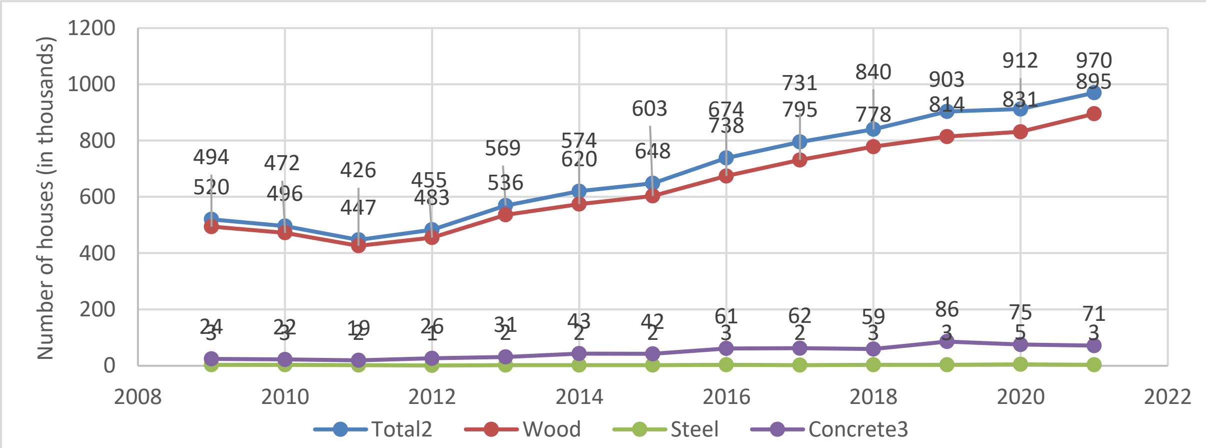

Figure 1: Type of Framing in New Single-Family Houses Completed in the U.S

IECC: The model for this case study was created to be compliant with the IECC codes for climate zone A2 which includes the Bexar County area in Texas, U.S. (See Table 1). To identify the technical characteristics (R-values, U-values) that are necessary for the building to be code-compliant, data was obtained by the International Energy Conservation Code (IECC). Because the case study of this work is placed in San Antonio, Texas, the IECC values for Zone 2 were used to determine a baseline for the energy performance modeling. Specifically, for the baseline model, an R-13 wall was implemented in the Energy+ software. Furthermore, the floor R-value was also R-13, and the ceiling was R-38. The windows used had a U-factor of 0.40 and a Solar Heat Gain Coefficient (SHGC) of 0.25.

Table 1: IECC requirements table for Texas climate zones.

	Windows			Insulation				Foundation		
	Fenestration U-Factor	Skylight U-Factor	Glazed Fenestration SHGC	Ceiling R-Value	Wood Frame Wall R-Value	Mass Wall R-Value	Floor R-Value	Basement Wall R-Value	Slab R-Value and Depth	Crawl Space Wall R-Value
Zone 4	0.32	0.55	0.4	49	20 or 13+5	8/13	19	10/13	10, 2ft	10/13
Zone 3	0.32	0.55	0.25	38	20 or 13+5	8/13	19	5/13	0	5/13
Zone 2	0.4	0.65	0.25	38	13	4/6	13	0	0	0

Regarding infiltration rates, the IECC code requires a maximum of 5 Air Changes per Hour (ACH) when tested at a pressure of 50 pascals for climate zone 2 (See Table 2). Therefore, for this study, the baseline simulations model infiltration rate was set at 5ACH.

Table 2: IECC requirements table for air leakage rates.

Air Leakage Rate	Climate Zone	Test Pressure
≤ 5 ACH	1-2	50 Pascals
≤ 3 ACH	3-8	50 Pascals

RS Means: Data on the specific characteristics of each wall assembly tested in this study and the associated costs of these assemblies were collected from the RS means publications, the industry's leading standard for construction practices, and cost estimates (John Wiley & Sons., 2012). To identify the industry standard of exterior wall assemblies, the RS means database was used. This database of standard construction practices was used to determine the wood-frame assembly design and all the construction costs associated with these wall assemblies. It can be seen in Figure 3, how the standard wood-frame exterior wall has many layers in which it can be designed and constructed. The wall variations, and their associated thermal properties, were used as simulation iterations of this study.

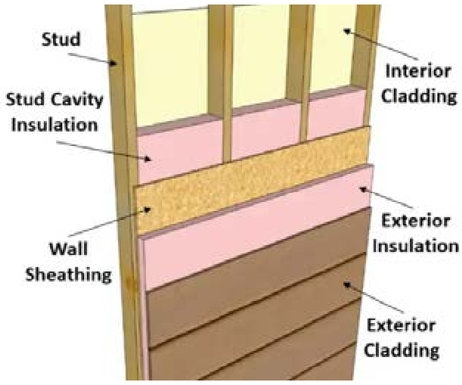

Figure 3: RS means, industry-standard exterior wood frame wall assembly (Builder's C., 2023)

2.3 Energy performance modeling

The energy performance modeling was done using the Design Builder software. Design Builder includes Energy Plus (*Energy Plus*, n.d.) which allows us to quantify the energy consumption and therefore the energy savings of the building. EnergyPlus is funded by the U.S. Department of Energy's (DOE) Building Technologies Office (BTO), and managed by the National Renewable Energy Laboratory (NREL)

The building models were designed to be identical with the exception of the construction of their external walls' insulation (from R-13 to R29) and the infiltration level of the building (From ACH 5 to ACG 1.25). The "baseline" model was designed to be compliant with the IECC code for the climate zone of Bexar County (A2) which includes San Antonio.

In order to perform the EnergyPlus simulation analysis for this study, first a 3D model of a residential house was designed in the DesignBuilder software (Figure 4). The general building design characteristics followed the "Prototype Residential Building Design for Energy and Sustainability Assessment" which was published by the National Institute of Standards and Technology (NIST) (Kneifel, 2012). The weather data required for the EnergyPlus energy simulations were downloaded internally via the DesignBuilder software for the geographical area of San Antonio, Bexar County, Texas.

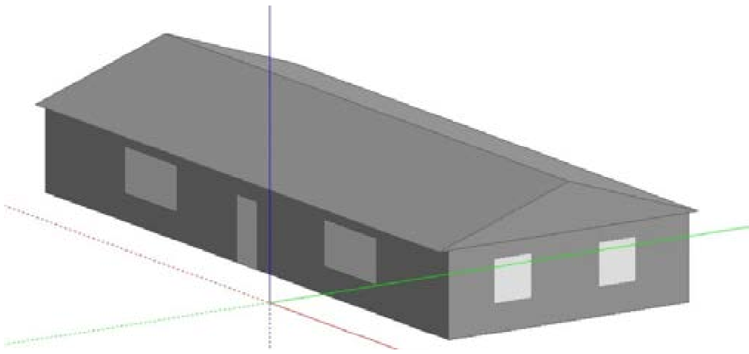

Figure 4: 3D axonometric view of wood frame building, in Design Builder software.

3. ANALYSIS AND RESULTS

3.1 Energy consumption results

Figure 5 depicts the monthly energy consumption for heating and cooling for the baseline model (IECC compliant) of the energy simulation analysis. For the summer months of June, July, and August, energy consumption for heating was minimal. This result was expected for the Warm-humid climate of this case study. Following a similar pattern, the cooling loads for the colder months (December, January, and February) were also minimal.

In the warm-humid climate of this case study, it is expected that the energy consumption for heating during the summer months of June, July, and August would be minimal. This is because warm-humid climates typically experience high temperatures and high humidity levels during the summer, reducing the need for heating. Therefore, the baseline model's energy consumption for heating during these months would be negligible.

Similarly, the cooling loads for the colder months of December, January, and February were also minimal in this case study. This can be attributed to the fact that colder months in warm-humid climates tend to have milder temperatures, reducing the need for cooling. As a result, the energy consumption for cooling in the baseline model during these months would be minimal.

These patterns of minimal energy consumption for heating in summer and cooling in winter align with the expected behavior in warm-humid climates. It indicates that the simulated baseline model's design, in terms of heating and cooling systems, is appropriately responding to climate conditions.

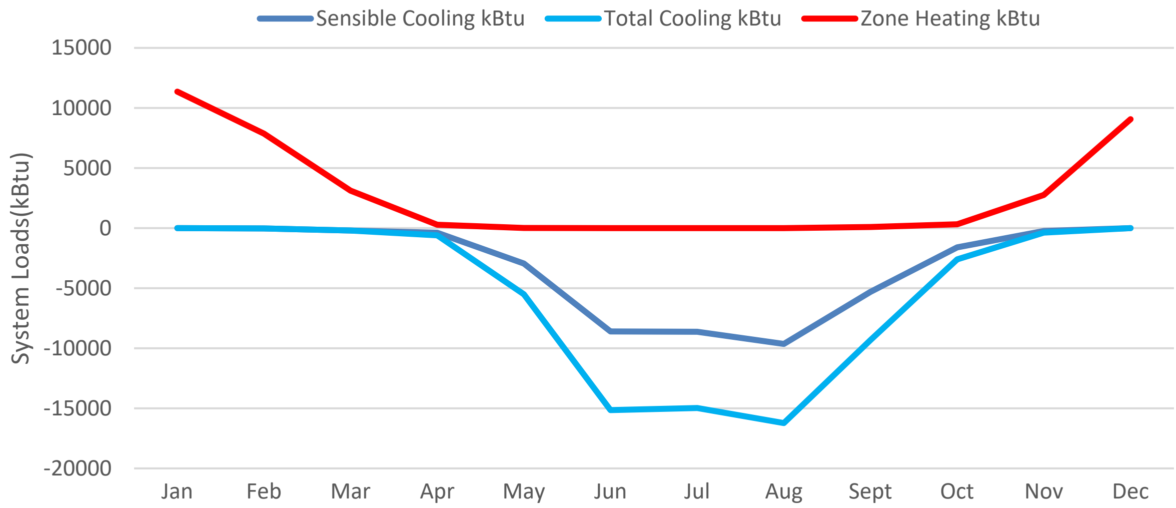

Figure 5: Monthly heating and cooling loads for the modeled house

Figure 6 showcases the effect different exterior wall iterations (R13 to R-29 and ACH 5 to 1.25) have on the cooling (shown in red) and heating (shown in green) of the house. As expected, because of the climate of this study, the cooling energy demands are overall higher than the heating energy demands, following a very similar ratio for all the wall iterations. Furthermore, Infiltration rates show a significant effect on the HVAC energy consumption compared to the Insulation levels.

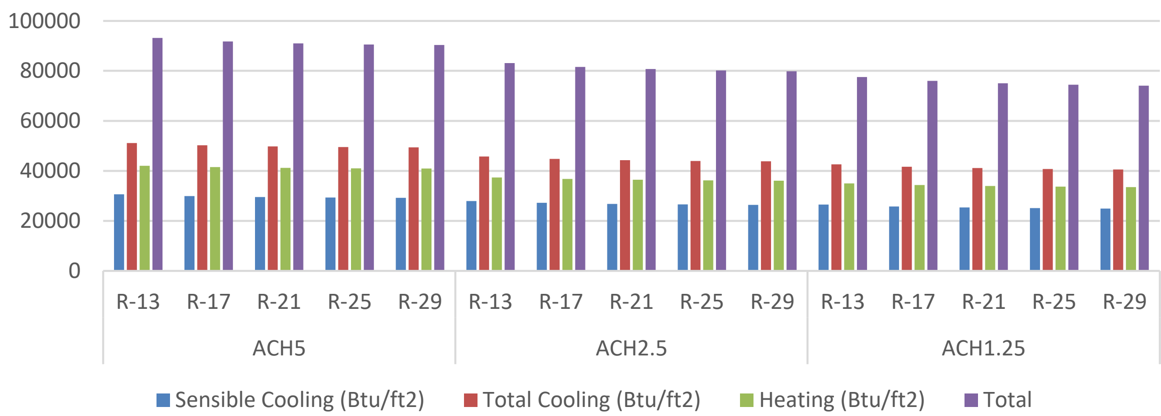

Figure 6: HVAC loads per square foot for different R-Value wall iterations

Figure 7 is a 3-dimensional graph that showcases the relationship between exterior wall R-value, building infiltration (ACH), and the overall energy consumption normalized by square foot (BTU/FT^2). As expected, a higher R-value lowers the energy consumption and a lower infiltration rate lowers the energy consumption. The colored strips of the graph represent energy consumption levels. This type of analysis allows us to easily identify and comment on the relationship between these 3 parameters, insulation, infiltration, and energy consumption. For example, the most effective level of lowering energy consumption is depicted with a light blue color at the bottom of the graph, and it represents a consumption rate of 75-77.5 kBTU/FT^2 for the building of our case study. It is apparent that a lower infiltration rate allows for this higher efficiency, even with the standard, minimum-compliant R-13 insulation. On the opposite spectrum of this graph, the inverse is also true- the building with a high, code-compliant infiltration rate is performing relatively poorly, despite the upgraded R-29 insulation. These findings quantify and validate the anecdotal rule of thumb of the residential building industry that *a good air sealing job with marginal insulation* is *far better than a good insulation job with poor air sealing.*

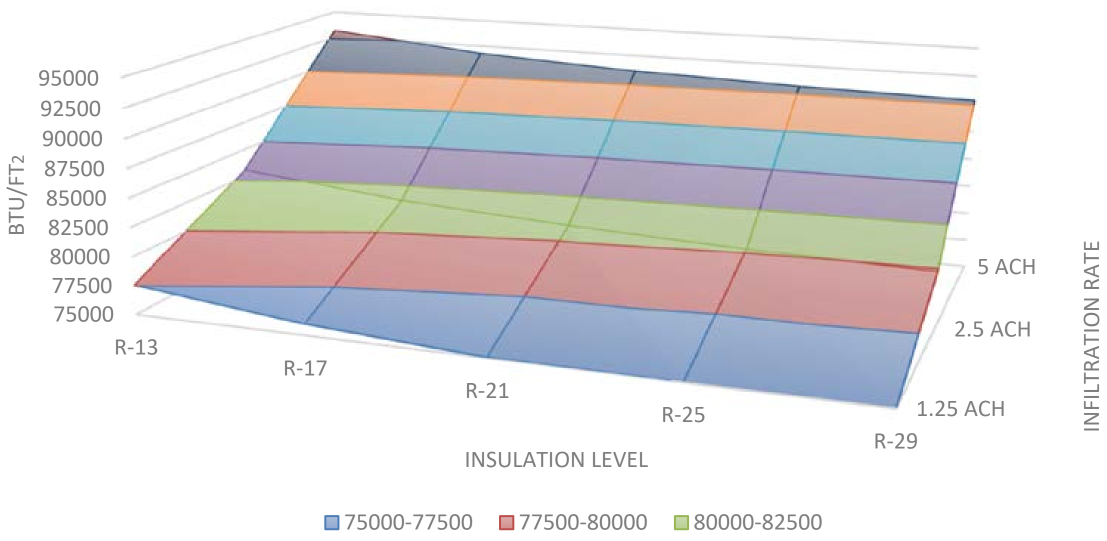

Figure 7: The effects of infiltration and insulation on energy consumption.

3.2 Cost Estimate and Return on Investment Results

The goal of this study is to provide an example of a valuable and applicable decision-making tool for many construction professionals in the pre-construction phase. Therefore, the energy consumption analysis of the previous chapter is supported by a cost analysis to evaluate the financial feasibility of these different wall assemblies. The cost analysis is presented in three parts. The first part of the cost analysis presents the cost estimating data, which includes the material and labor costs for the construction of these wall assemblies. This cost-estimating data was collected by the most recently published RS Means database(RS Means, 2023.). The second part consists in determining the operating cost analysis, where the energy consumption is converted into a monetary amount, based on the current average kWh cost of 0.14c for the area of Texas (electricityplans.com, 2023). The third and final part of the cost estimation analysis compares the initial construction costs with the operating cost savings to calculate the return on investment (ROI) and the payback period for each of these different construction updates.

3.2.1 Construction Cost Estimation

In order to properly quantify the construction cost of the different wall assemblies of this study, RS Means data was used, which includes both the material cost and the labor cost. There are a number of exterior wall construction methods that can be used to reach the R-values considered in this study. However, only the most commonly used methods of insulation practices were used for this analysis. The two most common types of insulation are Batt insulation and rigid board foam insulation. Furthermore, as mentioned before, this study focuses on the most common framing type for the U.S. market, the wood-frame wall. Therefore, the geometric limitations of the wood frame wall also affected the cost estimation analysis. Specifically, the maximum R-value that can "fit" inside a 2x4 framing wall using Batt insulation commonly found in the market is R-13 or R-15. That results in an increase of stud thickness from 2x4 to 2x6 in order to reach the values of R-25 and R-29. The cost associated with the thicker stud wall is taken into account for the cost estimate. Furthermore, a combination of Batt insulation and rigid board insulation is used to reach the specified R-values. This is a common construction practice in the industry. The last two rows of Table 3 show the total cost of insulation as well as the cost differential between the enhanced insulations (R-17 through R-29) with respect to required insulation per IECC Code (R-13).

Table 3: Cost Estimating data for exterior wall framing and insulation.

	R-13	**R-17**	**R-21**	**R-25**	**R-29**
Framing type	2X4,	2X4	2X4	2X6	2X6
Batt Insulation	3.5", R13	3.5", R13	3.5", R13	6", R21	6", R21
Exterior Board Insulation	-	1", R4	2", R8	1", R4	2", R8
Framing type cost (L.F.)	24.5	24.5	24.5	31	31
Batt Insulation cost (S.F.)	1.24	1.24	1.24	1.48	1.48
Board Insulation Cost (S.F.)	-	1.3	1.61	1.3	1.61
Total Cost / Linear foot	34.42	44.82	47.3	53.24	55.72
Total Cost for the house (U.S. $)	**4,268.08**	**5,557.68**	**5,865.2**	**6,601.76**	**6,909.28**
Additional cost from IECC code (U.S $)	**Baseline**	**1,289.60**	**1,597.12**	**2,333.68**	**2,641.20**

In the U.S., the common construction method used to reduce air leakage is the use of sealing tape (Building Energy Codes Program, 2018). Other methods can be used to reduce air leakage, the method used in this research project was Liquid Flash which can be applied in the building envelope (i.e.: bottom and top of the walls, around windows and doors, etc.) It was assumed that to reduce the ACH from 5 to 2.5 the Liquid Flash should be applied at the bottom and top of the walls and that to reduce the ACH from 2.5 to 1.25 the Liquid Flash should also be applied to windows and doors perimeter in addition to the walls. The last row of Table 4 shows the cost differential between the enhanced leakage (ACG 2.5 & 1.25) with respect to the required air leakage requirement per IECC Code (ACH 5) in the climate zone of the study.

Table 4: Cost Estimating data for air leakage sealing

			Cost	
	Length/Perimeters	**ACH 5**	**ACH 2.5**	**ACH 1.25**
Length of Wall on the Bottom (in contact with Slab)	178 FT	--	356.00	356.00
Length of Wall on Top (in contact with Roof)	178 FT	--	356.00	356.00
Windows	8 Windows (4'x'4) = 128 FT	--	--	256.00
Exterior Doors	2 Doors (3 x 6.5') = 38 FT	--	--	76.00
Additional cost from IECC code (U.S $)		**--**	**712.00**	**1,044.00**

3.2.2 Operating Cost Estimation

Figure 8 presents the energy saving result differential for each R-value step increase and for each of the 3 infiltrations (ACH 5, 2.5 & 1.25) categories tested. As expected, a higher R-value leads to more savings and a lower ACH level also leads to more energy savings. Furthermore, the operational savings in the case of poor infiltration rate (ACH5) are marginal. Specifically, for a greatly updated insulation to R-29, the operational savings are only 127 U.S. dollars, yearly, for the entire house of the case study. On the contrary, the improvements in infiltration rate, while maintaining the same R-13 insulation on the walls, lead to $ 453 and $ 702 in annual savings for ACH 2.5 and ACH 1.25 respectively.

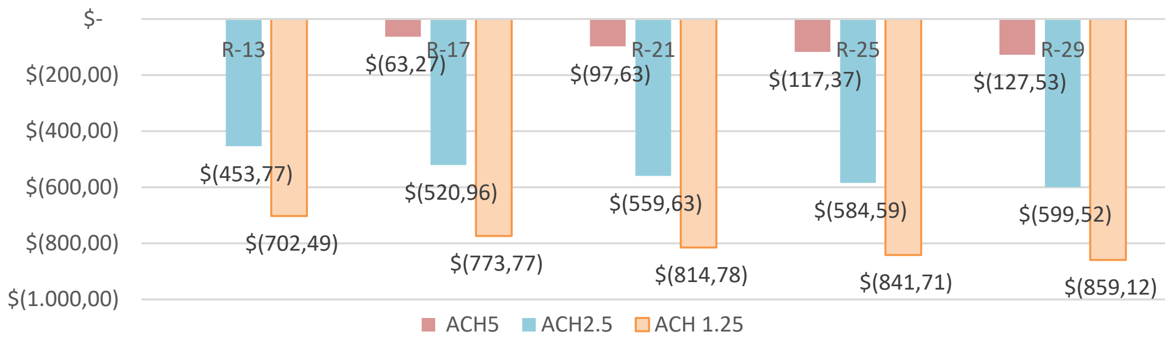

Figure 8: Annual Savings in U.S. dollars for the 1076 square foot house.

3.2.3 Return on Investment and Payback Period

The Return on Investment (ROI) and payback period analysis of this study showcases the importance of this type of methodology as a pre-construction decision tool. Figure 9 shows the ROI in bars and the payback period in lines. As shown in Figure 9, improving the R-value from R-13 to R-17 without improving the ACH results in an ROI of 4.9% and a payback period of 20.4 years (R-17 blue bar and line in Figure 9), while if the R-value from R-13 to R-17 is improved and the ACH is also improved from ACH 5 to ACH 1.25 the ROI is 33.2% and the payback period is 3.0 years (R-17 orange bar and line in the Figure 9). The same pattern showing a significantly better ROI and Payback period with lower ACH appears in all the other tester wall iterations of this study. The highest ROI was estimated to be 67.3% for improving the building's infiltration from ACH5 to ACH 1.25, without altering the insulation (R-13) of the exterior walls.

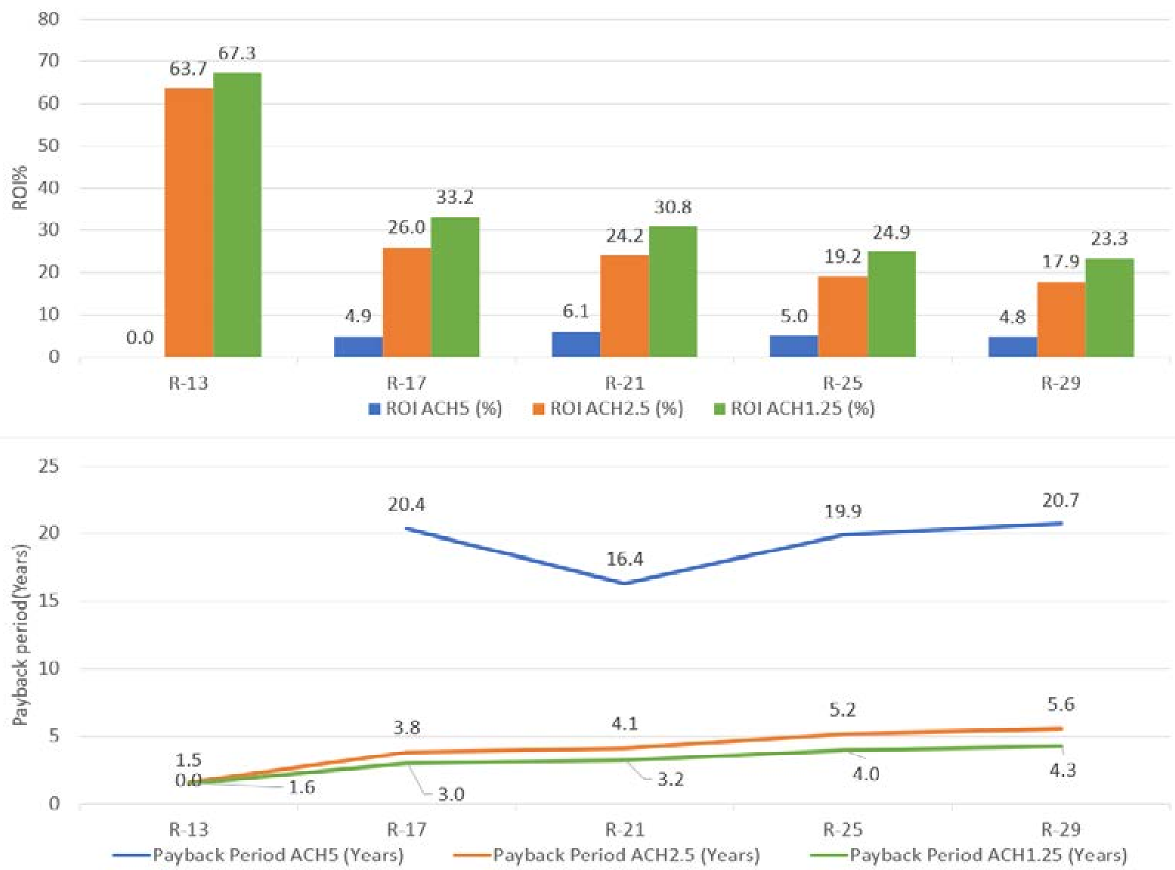

Figure 9: ROI and Payback Period

4. INTELLECTUAL MERIT

The intellectual merit of this work is to provide a greater understanding of the effects of the insulative level and the infiltration level on a residential building's performance. Furthermore, this analysis, combined with the construction characteristics and costs of the different wall assemblies can be used as a valuable decision-making tool during the pre-construction phase of a residential project. This work compared the energy-saving capability of upgraded exterior wall assemblies. Furthermore, the "upgraded" walls were tested under 3 different conditions of infiltration of the envelope of the case study. The results showcase the importance of infiltration levels for the overall performance of the residential case study. Furthermore, the methodology of this study can be replicated and scaled by construction professionals, in order to increase the economic competitiveness of a real project. Last but not least, a better understanding of the energy-saving capabilities of a better-built wall and the financial incentives presented in this study can promote a future of higher-standard construction methods for a myriad of houses across the globe.

5. SUMMARY AND CONCLUSIONS

This study highlights the importance of considering the construction and operating costs of residential buildings, with a focus on energy costs. Heating, ventilation, and air conditioning (HVAC) contribute significantly to a building's energy consumption. The research paper aims to analyze the trade-off between construction costs and operating costs by studying different exterior residential wall types in a warm-humid climate. The study uses quantitative methodology and a virtual case study to assess the impact of insulation and infiltration on energy consumption. The results highlight the importance of building infiltration on operational savings and return on investment (ROI) for different wall types. The study suggests that energy conservation regulations, such as the International Energy Conservation Code (IECC), could be revised to reduce energy consumption and greenhouse gas emissions.

In the study's climate, cooling energy demands are generally higher than heating energy demands, with a consistent ratio across different wall designs. Additionally, the infiltration rates, or the amount of air leakage, have a more significant influence on HVAC energy consumption compared to insulation levels.

Higher R-values and lower infiltration rates result in lower energy consumption. It is evident that a lower infiltration rate contributes to higher efficiency, even with the standard R-13 insulation. On the other hand, a building with a high infiltration rate, despite having upgraded R-29 insulation, performs relatively poorly. These findings support the industry belief that good air sealing with minimal insulation is superior to good insulation with poor air sealing.

The differential energy savings for each step increase in R-value and for each of the three tested infiltration categories. As expected, higher R-values result in greater energy savings, and lower air changes per hour (ACH) levels also lead to more savings. It is noted that the operational savings are minimal when dealing with poor infiltration rates (ACH5). Specifically, for a significant insulation upgrade to R-29, the yearly operational savings for the entire house in the case study amount to only $127. In contrast, improvements in infiltration rates, while maintaining the same R-13 insulation on the walls, result in annual savings of $453 for ACH2.5 and $702 for ACH1.25.

The results of the study highlight the significance of utilizing the ROI (Return on Investment) analysis as a decision-making tool during the pre-construction phase. The data presented in the study demonstrates the impact of different factors on ROI. For instance, with a consistent R-value wall of R-17, the ROI is calculated to be 4.91% for a poorly air-sealed example (ACH5), while it significantly increases to 33.13% for an improved air-sealing example (ACH1.25). This pattern is observed across all the tested wall iterations in the study. The study also identifies the highest ROI, estimated at 186.93%, for enhancing the building's infiltration rate from ACH5 to ACH2.5 without making any changes to the insulation of the exterior walls. These findings emphasize the importance of considering air sealing measures in order to maximize the return on investment, as it can have a substantial impact on energy savings and overall financial benefits. The study's distinctive contribution lies in its exploration of the typically overlooked aspect of infiltration rates in pre-construction building considerations, shedding light on the benefits of including these rates for a more holistic analysis of a building's performance.

Future work to build upon this research includes conducting a comparative study in different climate zones and with multiple building types and geometries to analyze the trade-off between construction and operating costs; conducting long-term monitoring of building performance to assess the actual performance of different wall designs over time; investigating the impact of occupant behavior on energy consumption; conducting a Life Cycle Costing (LCC) to evaluate the economic viability of different wall types; exploring the integration of renewable energy systems into residential buildings; focusing on retrofitting existing buildings to improve energy efficiency; and conducting a sensitivity analysis of parameters to determine their influence on energy consumption and ROI. Additionally, analyzing energy conservation regulations and providing policy recommendations for improving energy efficiency in residential buildings.

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BUILDING INFORMATION MODELLING (BIM) FOR CONSTRUCTION SUPPLY CHAIN: A SCIENTOMETRIC ANALYSIS

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ABSTRACT: *The automation and innovation have impacted Architecture, Engineering and Construction Industry, particularly when transitioning from traditional or conventional methods of construction to modular or Industrialized Building System (IBS). Thus, to ameliorate the processes surrounding built environment, researchers have been interested in the BIM's integration into construction industry. To ensure BIM's adoption and integration into construction supply chain, supply chain's management and procurement, we need to have an extensive comprehensive research base regarding global outlook of BIM's relation with supply chain. The purpose of this study is to identify global scientific research patterns and trends related to BIM's role in supply chain, by performing scientometric analysis. The scientometric analysis will help us analyze the work being done in this field and whether a significant literature exists that supports or helps in adoption of this idea. Most of the already existing research on BIM is performed on various other aspects of BIM like infrastructure sustainability, green buildings, design, framework, management of facilities and other BIM related managerial aspects. Thus, it is highly imperative to systematize and analyze the existing global scientific literature research to identify the global trends and frontiers on current BIM's relation with construction supply chain. Not only this would pave the way towards identification of current relevant literature but would also lay down the foundations for digital transformation in construction.*

KEYWORDS: *Building information modelling (BIM), construction, digitalisation, procurement, scientometric, supply chain management*

1. INTRODUCTION

The concept of integration of services is not new, over the past several decades this concept has been applied in various industries. However, integration in construction supply chain is still lagging as opposed to other sectors. There are several reasons behind it, including complexities in construction processes owing to the fragmented procurement processes, multiple project stakeholders and several other challenges. The instability and fragmentation occur when supply chains are temporarily created or setup for each individual one-off construction projects. (Papadonikolaki, et al., 2015). Meanwhile, Building Information Modelling (BIM) is a kind of technology that can collect, create, impart, and share accurate information among different stakeholders of construction supply chain. BIM is equipped and able to tackle operational, organizational, and other technical complexities in the construction supply chain. BIM not only enhances visualisation, design coordination and construction sequencing but also aids in construction processes through its various built-in features. These features include clash detection visualisation, scheduling and controlling capabilities. (Rathnasinghe & Kulatunga, 2019).

However, BIM's impact on challenges, faced by construction supply chain (CSC) at organisational level, is not thoroughly researched. The integration of BIM and CSC are still quite theoretical and conceptual, lagging in substantiated research. Only after extensive research and observing BIM's impact on the construction supply chain and its management, we can be fully assured of its contributions to the CSC. These gaps and voids in research thus need to be further explored. Thus, the following literature review will focus on the BIM's role and contributions so far to the CSC and its management. The literature review will also shed light on the underlying problems and background in the supply chain processes (Le et al., 2022). The research proposal has immense significance in terms of contributing to the theoretical knowledge related to the problem statement. The author believes that the

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Syed Haseeb Ahmad, Melissa Chan, Wei Yang, Hongyu Jin, Amirhossein Heravi, *Building Information Modelling (BIM) for Construction Supply Chain: A Scientometric Analysis,* pp. 477-488, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.46

need for this proposal is highly imperative as it further compliments the existing knowledge in context of BIM's multi-dimensional relations to construction supply chain at large and procurement.

The idea of construction supply chain has been around for a while now but still the constraints and challenges exist in construction supply chain owing to its uniqueness in each individual project. That means, every project being delivered is different in some ways from other projects rendering it difficult for integration to happen. This further tells that the construction supply chain is not strongly tightened interrelated process but a loose system which despite being important to global economy, is somewhat inefficient and untrustworthy. Thus, the research gap exists when it comes to addressing the issues (Papadonikolaki, et al., 2015). Moreover, if we narrow down the supply chain of Architecture, Engineering and Construction industry to mere procurement, again we'll find many unanswered problems. Integrating BIM with project delivery contract methods should ideally give rise to some new contract types specific to BIM usage but that hasn't been done yet and is a largely unexplored area.

2. LITERATURE REVIEW

The late twentieth century saw an evolution in logistics and supply chain management. This evolution had a direct impact and affected the construction supply chain and its management, due to its importance and magnitude. Since then, several problems and shortcomings in the construction supply chain management have been identified by the researchers involved in this field. Many problems were identified such as incoherence, lack of integration and inefficiency of the procurement or supply chain process (Khalfan et. al., 2015). A report on commercial construction industry highlighted that the mega projects take almost 20 percent more time to get completed than their scheduled completion date (McKinsey & Company, 2015). The report proclaimed that the construction industry still lagged in adopting innovative technologies when it came to information sharing about projects.

BIM can play a pivotal role in data collection, integration, and provision. The goal is to obtain or gather data which is accurate enough that it can be channeled to other projects to aid or assist in the building processes including Construction Supply Chain. This includes the gathered data that can link the mega scale projects and can be modelled using Building Information Modelling systems (BIM), and then exploring further ways to link these information and models to the construction supply chain (Wang et. al, 2017). To help everyone involved to have a better understanding and clarity of the overall project, the data that is already gathered in the BIM system can help in driving labour and material requirements hence assisting in a construction supply chain management (Wang et. al, 2017).

The approaches related to BIM and supply chain management revolve around supply chain integration with BIM to enhance and improve construction processes. Hence, it is believed that BIM can act as a catalyst for supply chain management adoption in construction (Wang et. al, 2017). The supply chain's integration is linked with both stakeholders and processes involved who are expected to coordinate and collaborate across various SC levels with long lasting trustworthy relationship. The researchers observed that supply chain stakeholders early risk management/allocation, involvement, participation, information technology investment and long-term procurement could further strengthen SC integration. (Getuli, et al., 2016). BIM can also help to enhance performances of mechanical, engineering, and plumbing aspects of the project. This can be done only with the stakeholder's cooperation, that means, early joint planning, joint decision making and operations. Construction supply chain partnership can be helped by Building Information Modelling through data-information sharing, trust building and enduring long-term commitment (Le et al., 2022).

During the early days of BIM development and while it was undergoing further technological advancement, one of the associated areas of interest was supply chain procurement and legal aspect of BIM. During early 21st century the BIM advocates observed that the two of the major hinderances in potential data sharing through BIM's platform; are legal constraints and varying frameworks of contracts. These two were seen to be obstacles in putting BIM in practice. Some of the key issues that surfaced include roles and responsibilities of individual stake holders being affected by use of BIM, liability and copyright issues associated with the BIM models, sharing of BIM's data and model ownership, and stakeholders focusing more on their individual components of the project rather than giving due consideration to the bigger picture of process (Holzer, 2015).

3. METHODOLOGY

This study aims to identify research patterns and trends about the global BIM research and how it is related to construction supply chain, construction supply chain management, and procurement in AEC industry. The research question focusses on how BIM is related to or being utilized for construction supply chain, supply chain management at large and procurement. The research method revolves around devising a framework of research design that defines and outlines the criteria for scientific databases, rules of search, defining data curtain, retrieving, processing, and analyzing of preliminary and final datasets. Therefore, this study employs the scientometric method, that is the sub-field of bibliometric analysis that is concerned with analysis and measuring of scientific literature. Bibliometric analysis can be defined as quantitative and statistical analysis of research data like journal publications, articles, and their patterns to identify the impact of those publications as well as to identify further research trends or patterns (Iftikhar et. al., 2019). The concept of bibliometric review was said to be introduced by Pritchard in 1969, who argued that this form of analysis had the potential to provide comprehensive insights into the research literature. (Pritchard, 1969). Fig. 1 outlines what would the scientometric analysis and mapping process would entail at each stage of the implementation. It illustrates what would be included at each step of this research project.

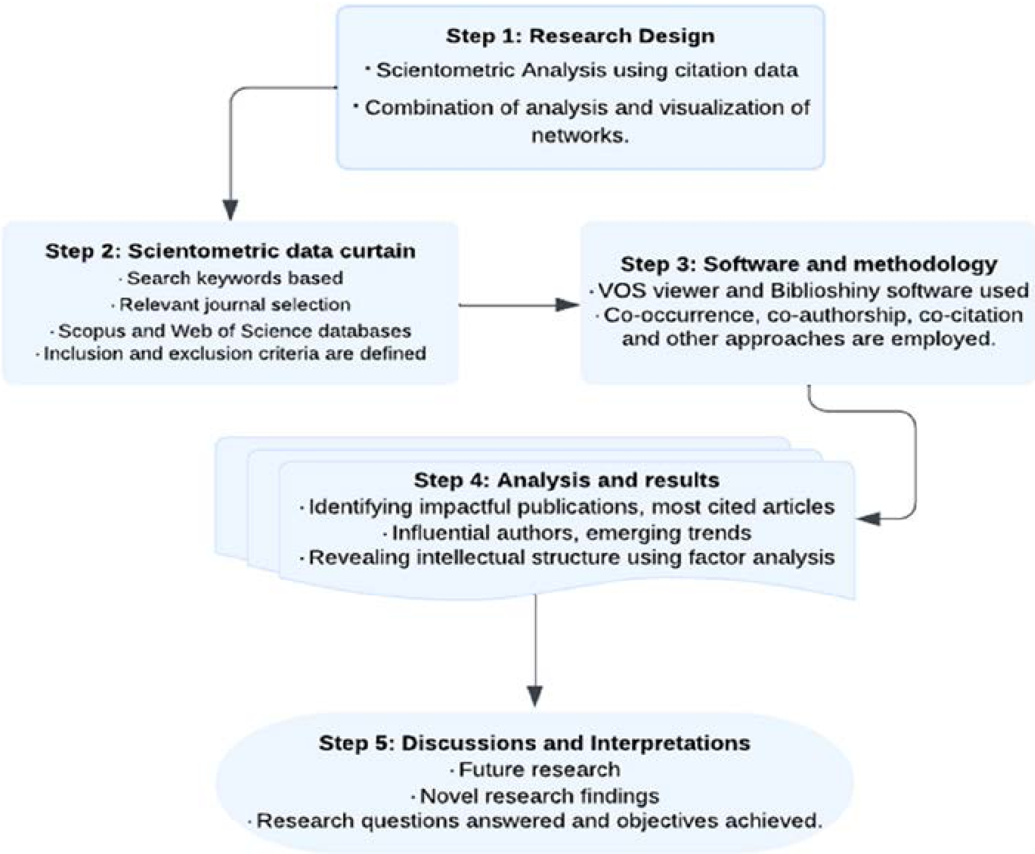

Fig. 1: Scientometric analysis and research mapping process

4. RESULTS AND DISCUSSION

Scientometric analysis was analyzed using several software as discussed and explained in research methods. The first analysis will revolve around outlining analytics related to Co-Authorship (type of analysis) and Authors (unit of analysis). The visualization results of 176 scientific documents retrieved from 'Web of Science' database, which were fed to VOS viewer. Hence, a visualization of co-authorship network was developed to analyze authors that had accounted for scientific research related to Building Information Modelling's role in procurement of construction projects, amelioration of construction supply chain and playing part in supply chain's management.

4.1 Visualisation Using VOSviewer

The VOS viewer was set to ignore publications which had large number of authors (maximum level set at 25 authors). The author's threshold with minimum number of documents was set at 2, whereas the minimum number of citations of an author were set to 1 citation. After applying the analytical functions, out of 464 authors, 46 authors met the threshold. These 46 authors had accounted for the most documents and citations in this respective research area. The table below outlines the data regarding these authors. The analysis reflects the most productive authors who had made significant research contributions to Building Information Modelling's role in AEC industry, especially, the areas related to supply chain management and procurement. As shown in Table 1, the 3 most productive researchers were found to be Chong, Heap-yih (7 documents,146 citations), Wang, Xiangyu (6 documents,142 citations) and Love, Peter (4 documents,124 citations). This was followed by authors Grilo, Antonio (3 documents, 95 citations), Jardim-goncalves, Ricardo (3 documents,95 citations) and Lee, cen-ying (3 documents, 94 documents).

Table 1: Publications and citations per author

No	Author	Documents	Citations
1	chong, heap-yih	7	146
2	wang, xiangyu	6	142
3	love, peter e. d.	4	124
4	grilo, antonio	3	95
5	jardim-goncalves, ricardo	3	95
6	lee, cen-ying	3	94
7	sing, chun-pong	2	75
8	matthews, jane	2	66
9	hosseini, m. reza	3	46
10	eadie, robert	2	33
11	edirisinghe, ruwini	2	32
12	skibniewski, miroslaw j.	2	31
13	mahdjoubi, lamine	2	27
14	rowlinson, steve	2	27
15	holzer, dominik	2	26
16	vass, susanna	2	21
17	zhou, jingyang	2	21
18	cheng, jack c. p.	3	19
19	das, moumita	2	19
20	ciribini, angelo l. c.	2	15
21	edwards, david john	2	15
22	mahamadu, abdul-majeed	2	15
23	scaysbrook, stephen	2	15
24	meng, xianhai	2	14
25	joseph-akwara, esther	2	12
26	law, kincho h.	2	12
27	gaterell, mark	2	10
28	lee, cen ying	2	8
29	tezel, algan	3	7
30	jin, ruoyu	2	7
31	li, haijiang	3	6
32	lindblad, hannes	3	6
33	ren, guoqian	3	6
34	abrishami, sepehr	2	6
35	abu-samra, soliman	2	6
36	chaabane, amin	2	6

37	phuoc luong le	2	6
38	thien-my dao	2	6
39	mejlaender-larsen, oystein	3	5
40	fai, s.	2	5
41	sacks, rafael	2	4
42	ariffin, hamizah liyana tajul	2	2
43	mustaffa, nur emma	2	2
44	papadonikolaki, eleni	2	2
45	he, dandan	2	1
46	li, zhongfu	2	1

4.2 Network Visualisation

The network visualisation is shown in Figure 2 Network Visualization Co-authorship, that illustrates the total link strength of 60 with 32 links and 25 clusters. The co-authorship link strength refers to the collaboration strength of the authors. The nodes represent the author whereas thickness or size of nodes represent the documents. The edges or links refer to co-authorship collaboration between the authors, the thicker the lines, the stronger the collaborations. As mentioned previously, there are a total of 25 clusters, but we will analyse only top 3 clusters as they are indicative of strong collaborative research authorship between them. Fig. 2 shows the biggest cluster, cluster 1, is denoted by red colour and comprises of 5 top productive others; Chong, heap-yih being the most productive of the lot with total link strength of 12, 7 documents and 4 links (1 link with each other author in the cluster 1). Following Chong is Wang, Xiangyu with 3 links with Chong, Lee and Cin-Yeng. Wang had co-authored total of 6 documents with a total link strength of 10.

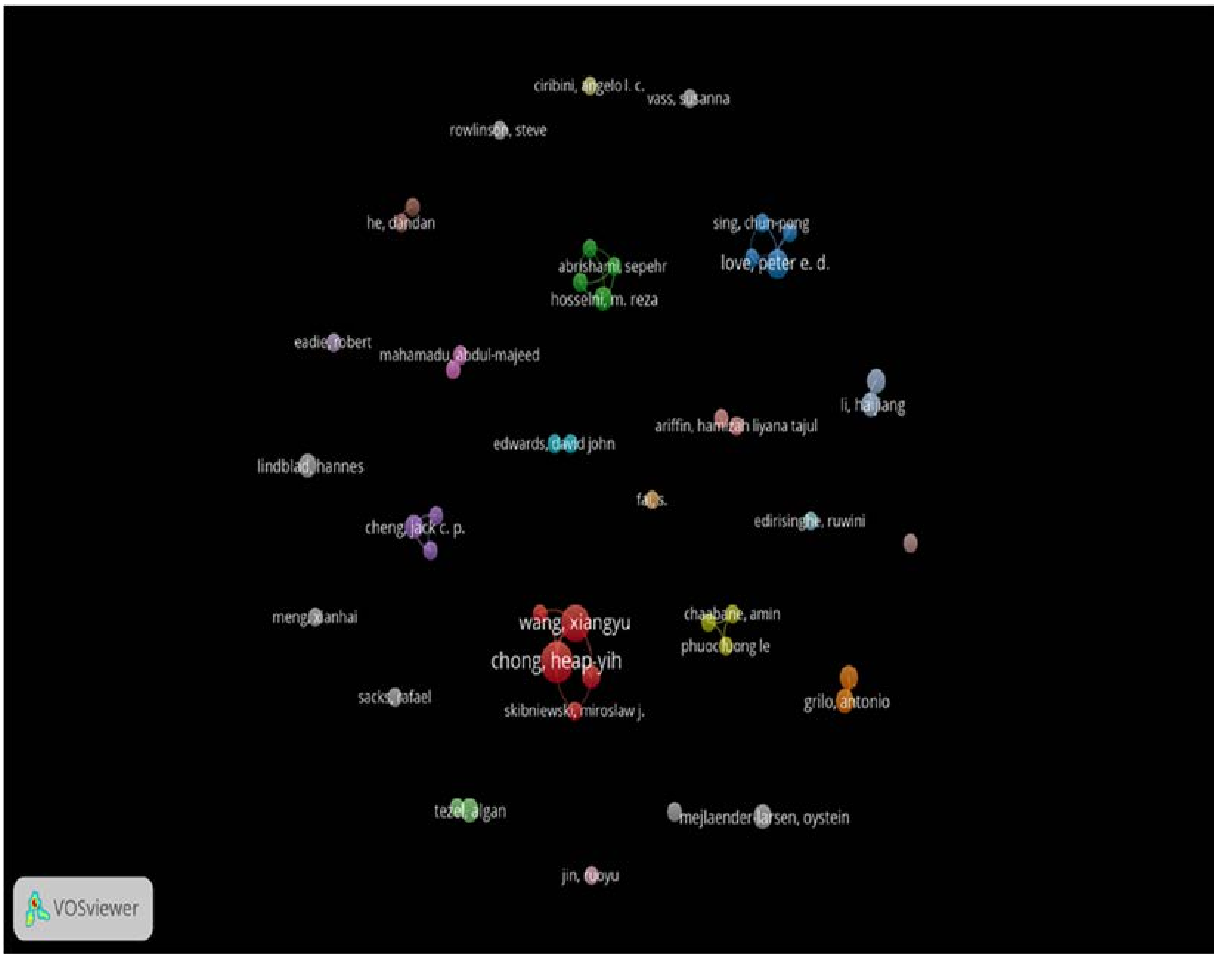

Fig. 2: Network visualization co-authorship

The cluster 2 consisted of 4 authors, 2 of these authors, Abrishami. and Abu-samra had strong collaboration links between them in terms of co-authorship of publications as both had published 2 documents but their total link strength was 5 each and had links with each other as well as 2 other authors in the cluster. The other author Husseini had the same total link strength of 5, however, he had authored 3 publications only with each of the fellow authors in its cluster. However, in blue colored cluster 3, author Love, Peter's node and edges were indicative of very strong collaborative effort with rest of the authors in the cluster. Love had total of 4 documents with total link strength of 6 and 4 documents thus depicting significant co-authorship whereas rest of the 3 authors namely Sing, Chun-pong, Matthews, Jane and Zhou, Jingyang had each collaborated 2 documents and had link strength of 4.

4.3 Co-occurrence keyword analysis

Over the past couple of years there has been increased involvement and information about Building Information Modelling in every aspect of Built environment and AEC Industry at large. This has led to evolvement of numerous themes and topics in research related to BIM's involvement in the construction industry. In this section we'll be discussing analytics surrounding co-occurring keywords in our results' dataset. Keywords play an important role by serving as reference point, aiding the contents' description and conceptual understanding in research literature. (Akinlolu, et al., 2020). Hence to perform co-occurring analysis of keywords, data from Web of Science was imported into VOS viewer. After feeding the said data into VOS viewer, the threshold for minimum occurrence of a keyword was set to 5 keywords. Hence, out of 781 keywords, 34 met the threshold. Table 2 tabulated the most recurring or co-occurring keywords in decreasing order of occurrence.

Table 2: Keyword occurrences

No	Keyword	Occurences	Total link strength
1	bim	57	150
2	building information modelling	33	100
3	management	29	108
4	procurement	28	80
5	construction	24	66
6	performance	23	89
7	design	22	86
8	framework	22	90
9	implementation	21	94
10	model	21	84
11	collaboration	17	53
12	building information modelling	15	29
13	building information modelling (bim)	15	36
14	building information modelling (bim)	15	37
15	information	15	51
16	innovation	13	65
17	project management	13	52
18	system	13	53
19	projects	12	57
20	industry	10	57
21	technology	9	42
22	sustainability	8	27
23	adoption	7	34
24	construction industry	7	27
25	construction supply chain	7	14
26	information modelling bim	7	39
27	construction projects	6	27
28	interoperability	6	20
29	systems	6	25
30	infrastructure	5	14

31	ipd	5	14
32	lean construction	5	19
33	prefabrication	5	18
34	simulation	5	27

The degree of co-occurrence is determined by similarity of keywords as well as their proximity to one another. The 34 top productive and repetitive keywords from 176 research publications produced total of 4 clusters as shown in the figure below. The biggest cluster of all was cluster 1 with 13 keywords and is denoted by red color. The intertwining of links and proximity of nodes reinforces the point that the various aspects of construction industry and built environment are directly proportional and related to Building Information Modelling.

4.3.1 Cluster 1

The first and strongest cluster had various keywords with strong and highly imperative correlation and literature's scientific structure thus helping in anticipating trends and establishing firm research base for future. As shown in Fig. 3, the first cluster had several keywords like building information model/modelling, project management, construction industry, lean construction, prefabrication, sustainability, and interoperability.

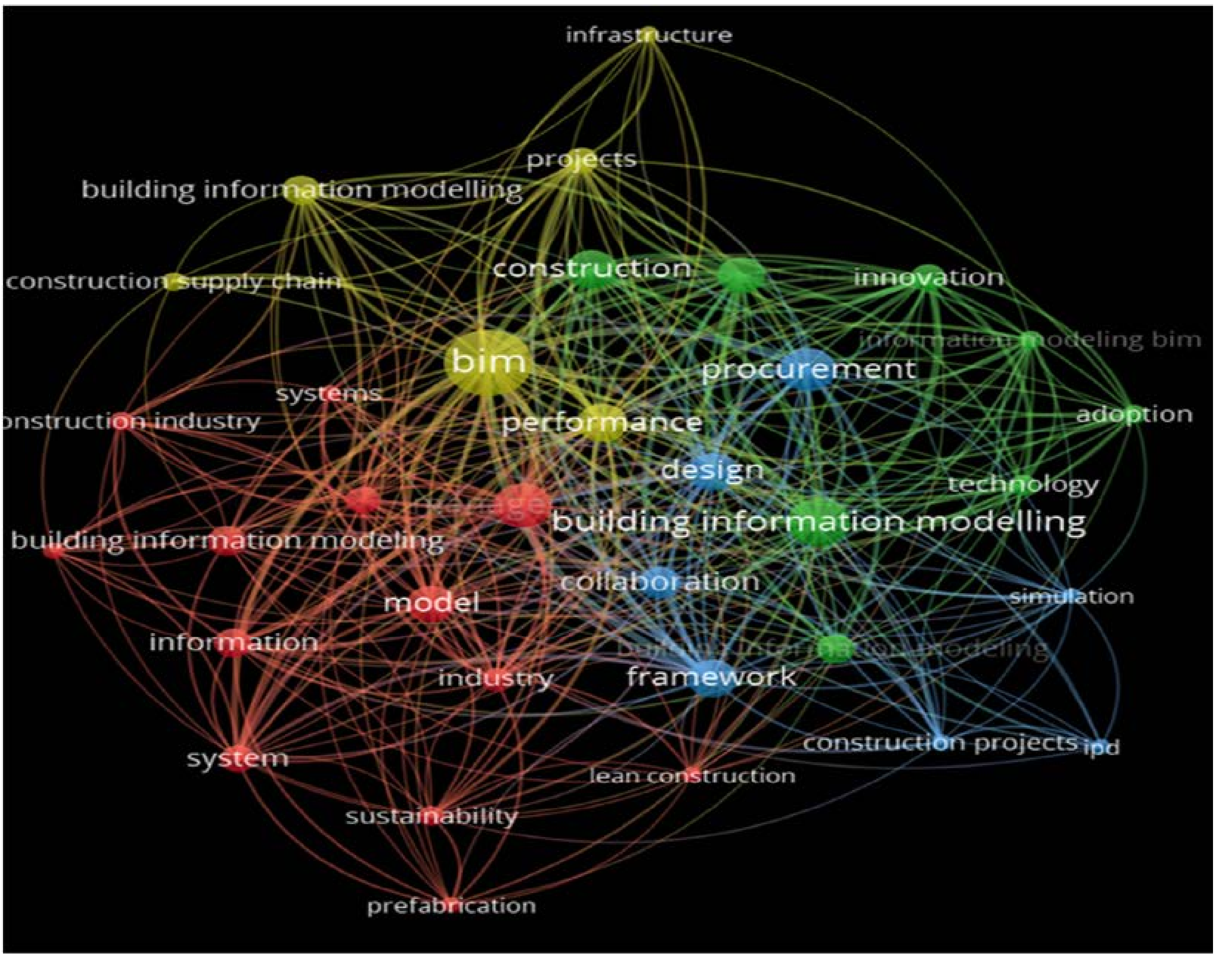

Fig. 3: Keyword co-occurrence network visualization

This cluster's keywords had most relatedness thus depicting that these areas of research in relation to BIM were most comprehensive. We'll also look at the overlay visualization of these clusters as well in the figure below. The cluster 1 had research conducted on its keywords from 2015 to 2017.38 average year. The keywords like 'lean construction' and 'prefabrication' were the latest with average year 2017 moreover both keywords had 5 occurrences each. This is indicative of the fact that although BIM's involvement with sustainability and industry is couple of years old, but still witch each passing year we are seeing innovative concepts being researched about in BIM's context.

4.3.2 Cluster 2

This cluster had some interesting terminologies like technology, innovation, implementation, and adoption along with the other repetitive keywords like "BIM", "construction" etc. As opposed to the cluster 1, this cluster had more recent research trends averaging between year 2017 to 2018. The keywords like "innovation" had strong links with "BIM adoption" and "construction collaboration". Thus, it is pertinent to note that there has been increased inclusion of innovation and adoption in hot areas of global subject literature around BIM and the strong edges in "overlay visualization" are indicative of increased research trends.

4.3.3 Cluster 3

The third cluster as shown in Fig. 4 revolved around keywords like "collaboration" (17 occurrences, 22 links and avg. pub. Year 2016.4), "construction projects" (6 occurrences, 16 links, avg. pub. year 2017.5), "design" (22 occurrences, 27 links, average year of publication 2016.80), "framework" (22 occurrences, 28 links and average year 2017), "procurement" (28 occurrences, 26 links, average pub. year 2016.19) whereas '"IPD or integrated project delivery" and "simulation" had 5 occurrences each with 14 and 19 links, and avg. pub. years. 2015.25 and 2016.5 respectively. Keywords like "framework", "procurement" and "simulation" were seen to be the most recent ones in this cluster, however, one common thing among all clusters is the strong link strength and proximity with the words 'BIM'. Based on centrality of nodes and strength of links, an inference could be made that these keywords play an important role in diversifying the BIM's research literature.

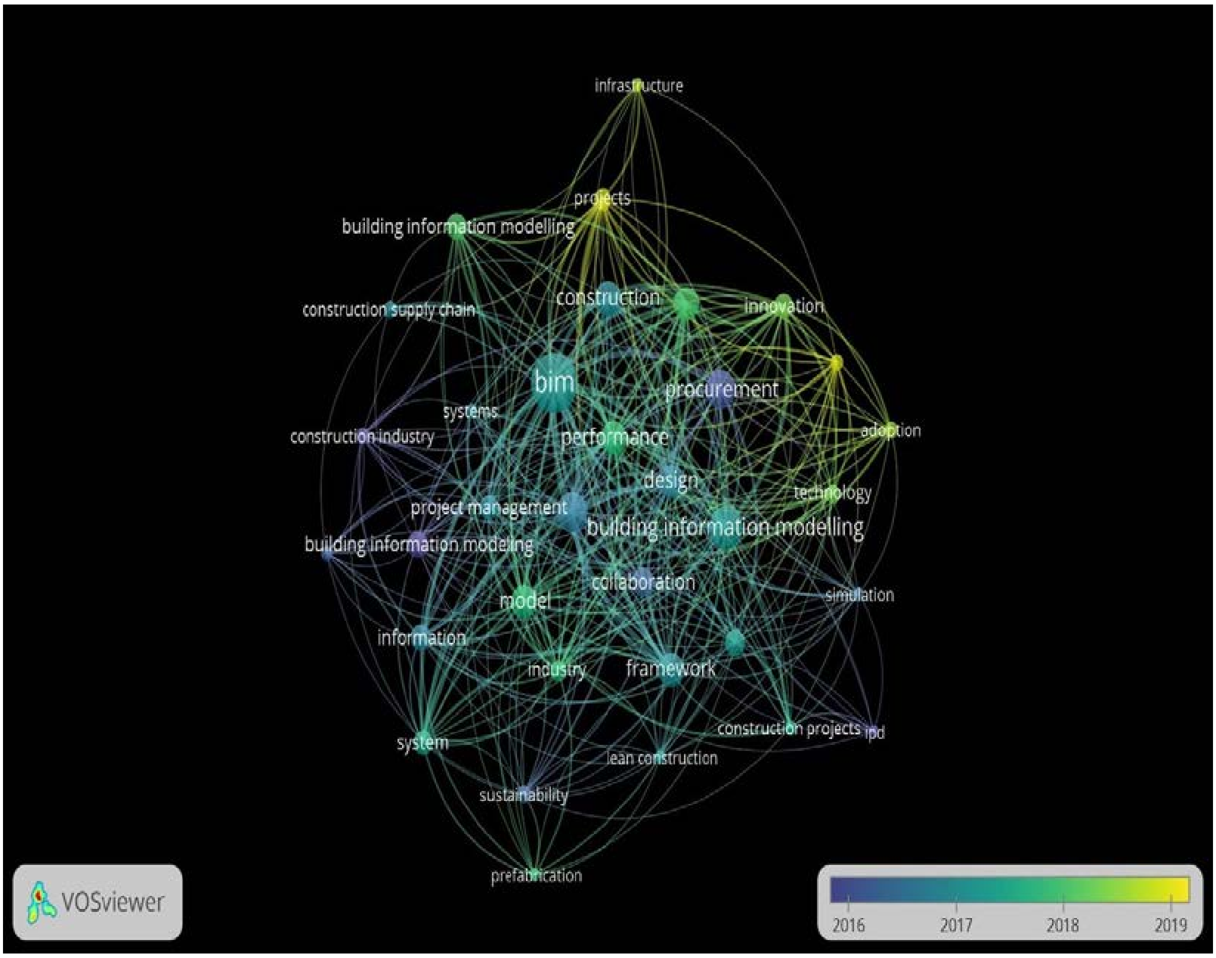

Fig. 4: Keyword cluster overlay visualization

4.3.4 Cluster 4

The last cluster had total of 6 keywords that included BIM, building information modelling, construction supply chain, infrastructure, performance, and projects. The green and yellow nodes (representing year 2017 and 2018) of these keywords reflect the latest research developments and collaboration in these respective fields. If we look at the item density visualization in Figure 5, item density visualization it tells us about the keywords density at a particular point and is represented by a color. The colors vary from blue to green to yellow. The closer the proximity of the keyword to the large number of other keywords and the larger the weight of those items, the more the color of that point is yellow. Hence, if we analyze the density visualization, it is self-evident that keyword "BIM" has bright yellow color and has proximity and relatedness with keywords like "performance", "procurement", "management", "design", "collaboration" and "construction". Since the word "BIM or Building information modelling" has been repetitive in each cluster thus not all same keywords have same density. For example, item density visualization in Figure. 5 illustrates "construction supply chain" in proximity with 'building information modelling' in top left corner thus reiterating the connection between the two.

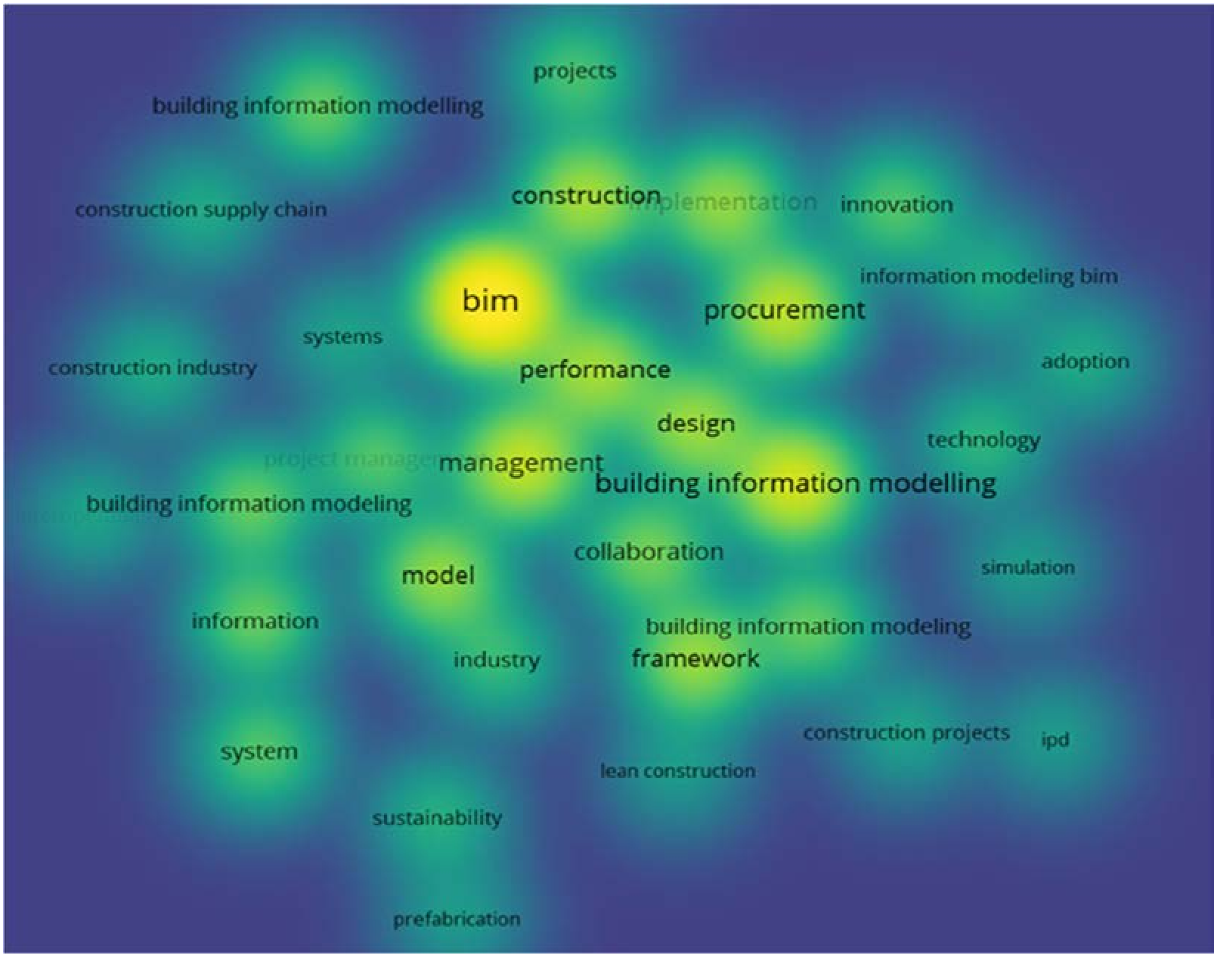

Fig. 5: Item density visualization

4.4 Collaboration network of countries

Consequently, the dataset produced comprehensive scientific mapping for us to analyze. The collaboration network of countries was pulled out and examined, as shown in Figure 7: Collaboration Network of Countries. The figure illustrates the biggest collaboration node being represented by UK having the strongest cross collaboration link with Australia. UK was seen to have a collaboration network with Australia, Luxembourg, Canada, South Africa, Ireland, China, Hong Kong, and Ireland. Whereas, after removing the isolated nodes several collaboration trios were identified. These trios included USA, China, and Israel. Moreover, to have a clear picture of social structure, a country collaboration map was prepared as shown in Fig. 6, that showed intercontinental collaboration on BIM usage in supply chain and construction industry.

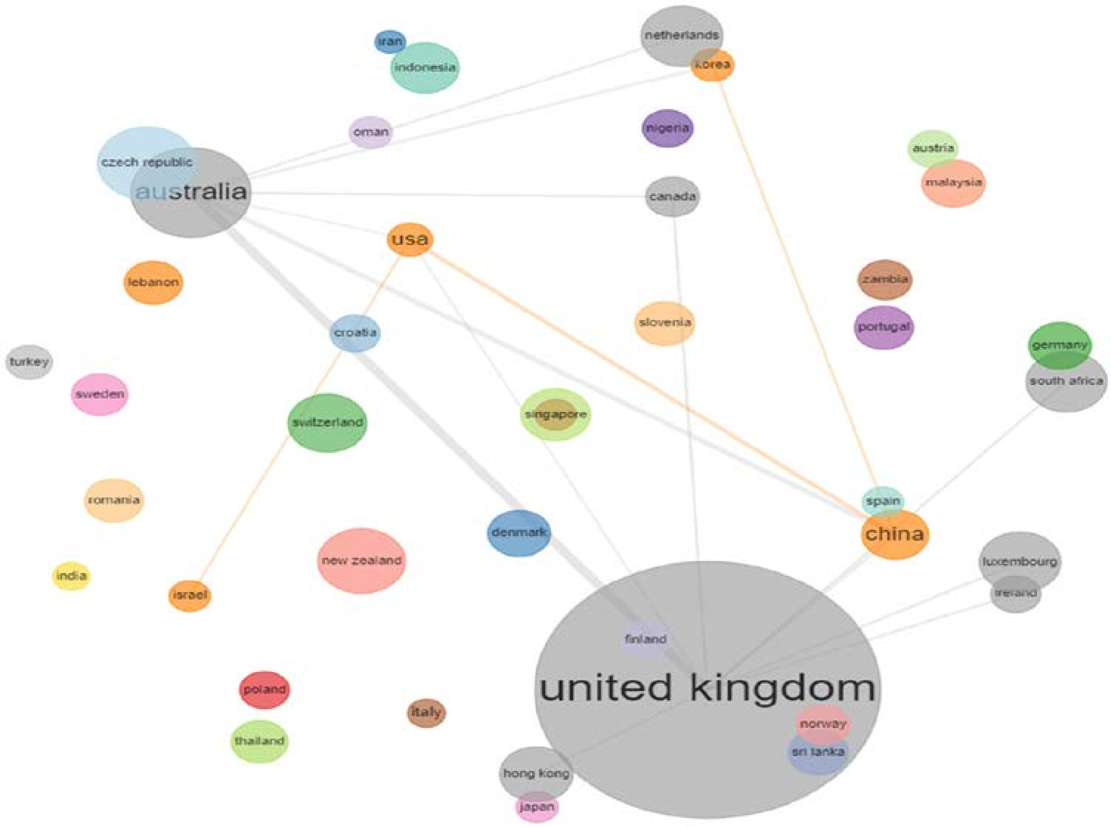

Fig. 6: Collaboration network of countries

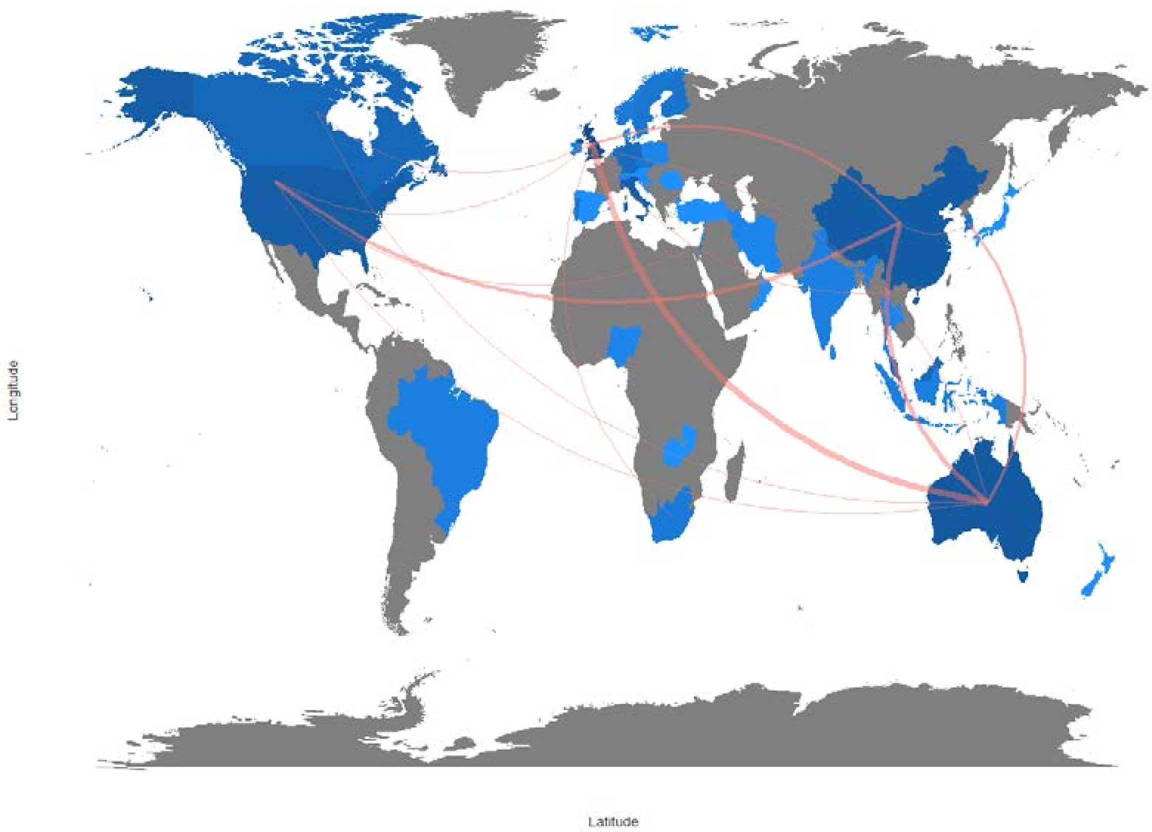

Fig. 7: Countries of collaboration

Fig. 7 shows there are three shades of blue clearly seen in the map. The darkest shade of blue seen between China, Australia, UK, and USA represent most productive contribution, whereas the thicker pink linkages depict the strength of collaboration. The lighter shade of blue comes second in production of scientific literature on BIM, construction supply chain and procurement.

4.5 Conclusions

The Web of Science database helped discover 176 relevant publications which were imported into VOS viewer and as per research objectives the co-authorship analysis were performed initially. The co-occurrence authorship analysis depicted various patterns. The strongest partnership cluster between authors comprised of 5 authors denoted by red color and had thickest edges thus had biggest impact. We can see the biggest cluster of 5 authors although had the strongest links and collaboration but still the average publication years were between 2014-2015. This explains that the only strong collaborations on BIM's relation with construction supply chain were done couple of years ago and are not recent. Whereas the yellow-colored clusters which are not only small in link strength and only consist of 2 or 3 authors, but also have less collaboration and occur isolated in the cluster, are the most recent ones. There is no robust or exponential growth in scientific research literature when it comes to BIM adoption into supply chain management, logistic and/or procurement. Thus, the future BIM research must be driven and molded towards these areas.

The second scientometric analysis was Co-occurrence of keyword analysis, which consisted of 4 keyword clusters, with Cluster 1 being biggest containing 13 keywords, followed by 8,7 and 6 keywords respectively. It was pertinent to observe that the word "Construction Supply Chain" only appeared once in a cluster, with 7 occurrences in cluster 4, with average publication year of 2017. The most recent or latest keyword cluster was seen to be 'adoption' (denoted by yellow) with strong links to other keywords like "technology", "information", "infrastructure", "management", "design", "framework" etc. Thus, a clear pattern can be observed here that the already existing research regarding BIM's adoption into infrastructure management and other fields is being explored but at the same time key area like supply chain is somewhat lagging. On the other hand, 280 publications from Scopus were exported to Biblioshiny for scientometric mapping purposes and collaboration network between the countries was analyzed. This was done to examine the global research patterns which would further help in identifying the parts of the world where lack of collaboration is significant. Hence paving the way for future researchers, belonging from those countries, to comprehensively explore into otherwise ignored BIM's associated aspects, particularly in construction supply chain.

The innovative contribution of this study is pertinent with the integration of BIM and CSC are still quite theoretical and conceptual, lagging in substantiated research. Only after extensive research and observing BIM's impact on the construction supply chain and its management, its contributions are clear to the CSC. Study gaps in previous research highlighted BIM's role on multi-dimensional aspects to supply chain. This study is highly imperative as it compliments the existing knowledge in context of BIM's at large and particularly in relation to construction procurement. Current challenge includes the creation of a consistent information flow that hasn't addressed BIM cooperation process among all construction stakeholders. Therefore, this study contributes towards addressing these practical issues by outlining a framework for the integration of BIM and CSC. An example of successful application of the relationship is when BIM acts as an information integrator while CSC is a secure environment for collaboration in real-world construction project. The BIM-based CSC multi-model integration framework is therefore crucial in identifying, analyzing, and making full use of the organisational, operational, and technical complexity. Additional real-world cases can be used to calibrate the model in the future to establish successful application of the relationship between BIM and the construction supply chain.

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E-PROCUREMENT IN THE AUSTRALIAN CONSTRUCTION INDUSTRY: BENEFITS, BARRIERS AND ADOPTION

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ABSTRACT: *A clear benefit of e-procurement technology in the construction sector is its capacity for in reducing waste and costs. Despite its successful adoption in other major industries, the take-up of e-procurement in the construction industry has generally been slow. A variety of barriers to adoption have been identified in literature, predominantly at an international level. Whilst the benefits of e-procurement are well-known and the challenges and barriers to the adoption of these systems in the construction industry has been well-documented, research into actual outcomes following the adoption of e-procurement systems through a case study analysis is limited. Tracking and measurement of adoption rates in the Australian construction industry is particularly scarce. To build upon and add to the existing body of contemporary literature, this study seeks to examine the adoption of e-procurement technologies in the Australian construction industry. As the Australian construction sector enters a period of high inflation, technologies such as e-procurement have a critical role in mitigating these price escalations. Understanding the barriers and opportunities for wider adoption of e-procurement in the Australian construction industry is also a clear benefit with its capacity for digital transformation in the construction sector.*

KEYWORDS: *E-procurement, technologies, digital transformation, construction, Australia.*

1. INTRODUCTION

The construction industry is one of the largest sectors in the Australian economy, employing some 1.03 million workers across 395,000 individual businesses (IBISWorld, 2021). The industry accounts for 9% of Australian Gross Domestic Product (GDP) with the total value of construction work done over the 12-months to December 2021 in the order of $214 billion (ABS, 2022). Procurement management is a well-established technique utilised by firms to drive sustainable competitive advantages during periods of economic turbulence (Hong and Kwon, 2012). Since emerging more than two decades ago, e-procurement technologies have increased significantly across many sectors (e.g., manufacturing, wholesaling) as both government and private firms have realised the benefits of e-procurement platforms, including, inter alia, increased transparency and accountability, improved sustainability, and cost savings (Deraman et al., 2019). The evolution of e-procurement platforms has evolved greatly over this period, growing from simple electronic-based systems to fully integrated, web-based platforms. Despites its successful adoption in other major industries, the take-up of e-procurement in the construction industry has generally been slow and low (Afolabi et al., 2019).

A clear benefit of e-procurement technology in the construction sector is its capacity to reduce waste and costs. For instance, e-procurement enables building and construction firms to more accurately review and cost projects at the procurement stage and enables more efficient management processes on-site. Furthermore, e-procurement enables clients to achieve more competitive pricing through contacting more potential suppliers without increasing overheads. Technologies such as e- procurement systems have a critical role in mitigating price escalations and while the challenges to the adoption of these systems in the construction industry has been well-documented, research into actual outcomes following the adoption of e-procurement systems is limited. Tracking adoption rates in the Australian construction industry is particularly scarce. To build upon and add to the existing body of contemporary literature, this study applied the science mapping approach into the area of e-procurement in construction. It aims to provide insight into the existing challenges, benefits, and adoptions rates of e-procurement in the Australian construction industry and seeks to provide recommendations for future adoption.

2. LITERATURE REVIEW

E-procurement is the use of the Internet to support the delivery of procurement tasks. More specifically, it is an aspect of e-Commerce that incorporates web-based applications and communication technologies to carry out

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)

Eleanor Hayden, Melissa Chan, David van Kan, Victor Arowoiya, Mohd. Amizan Mohamed, *E-Procurement in the Australian Construction Industry: Benefits, Barriers, and Adoption,* pp. 489-498, DOI 10.36253/979-12-215-0289-3.47

procurement activities such as sending and receiving tender information, submission of tenders, acquisition of materials, equipment and services, and payment of goods and services (Ibem and Laryea, 2015). A study conducted in the United Kingdom by Eadie et al., (2010) sort to identify the leading barriers and benefits in e-procurement. A survey of 775 construction organizations was conducted and revealed that the leading benefits were 'Process, transaction and administration cost savings', 'Convenience of archiving completed work', and 'Increased quality through increased accuracy'. These benefits support the findings of Brandon-Jones (2017) who suggests that the use of e-procurement can deliver significant operational benefits, including improved delivery accuracy, reduced transaction costs and greater control over organization procurement. Furthermore, Yevu and Yu (2019) found that drivers of e-procurement can be broken into seven categories: external drivers, project-level drivers, technological and process-level drivers, company-level drivers, individual-level drivers, service satisfaction drivers and sustainability concept drivers. Interestingly, they note that modern construction concepts such as sustainability and client satisfaction are influencing the adoption of e-procurement. Conversely, Eadie et al., (2010) identified the dominate barriers to e-procurement as 'Prevention of tampering with documents', 'Confidentiality of information', and 'Resistance to change'. Another study by Yevu et al., (2021b) categorized barriers into six groups: technological usability and evolution, security and unsupportive environment, culture, infrastructure, unethical practices, and financial and skills related.

A wide range of international studies has been undertaken, (Zunk et al., 2014; Ibem and Laryea, 2015; Afolabi et al., 2017, 2019; Tran et al., 2021) and found that whilst e-procurement is not a new concept in the varying industrial sectors, the construction industry has been slow in adoption compared to other industries such as manufacturing and retail business (Ibem and Laryea, 2015). These studies indicated the varying barriers and drivers e-procurement has on developing and developed economies. It has been discovered that the high cost and low access of Internet services in developing countries combined with lack of industry experience and training has had an adverse effect on initial uptake of e-procurement (Ibem et at., 2021; Tran et al., 2021). A common barrier found both in developing and developed countries was the lack of expertise and promotion of e-procurement (Yevu et al., 2021b; Zunk et al., 2014). Zunk et al., (2014) reports that some construction firms in Austria didn't know what e-procurement was let alone the benefits. Afolabi et al., (2017) states that the benefits of e-procurement platforms should not be overlooked. They note it is a viable tool for increasing productivity and empowering construction professionals to exercise greater control of the construction process. Aghimien et al., (2021) added that digitalisation offers solutions to consistent challenges of delivering projects over budget, beyond the expected timeframes and not to specification. It is evident that a large volume of international research exists relating to e-procurement within the construction sector.

Enterprise Resource Planning (ERP) systems have become commonplace applications in significant sectors. According to industry rankings and turnover, the top suppliers include SAP, ORACLE, Microsoft. ABAS, IFS and Step Ahead. Implementing BIM enables better project management, process efficiency, increased transparency, cost control, and real-time communication, just like with ERP systems. Additionally, the system may retain all technical information, drawings, and construction methods, and users can simultaneously work on different project phases throughout the course of the project's lifespan. BIM may be used to manage the technical elements of a building project as well as help with strategic procurement choices like choosing a contractor. There are many advantages of adopting ERP systems in the construction industry including automating procedures in client assistance, project management, cost predictions, employee management and procurement management through operational automation. Project management needs to be optimized since it is vital to the success of any construction company. Without good project management, the company would lose Clients and money. With all operational activities are automated by the ERP system, project management supervision is improved. ERP is a useful tool for cost estimation since it considers all important cost aspects, including materials, design, contracts, and transportation. Budgets for specific cost centres can be estimated and allocated to include overhead liabilities and even potential delays.

In the construction sector, successful project execution depends on efficient communication, in which ERP systems are enhancing communication. One issue that construction businesses frequently struggle with is maintaining strong departmental communication. Project schedules may be impacted by departmental disconnections that slow down operations and business processors. Employees may rapidly tell executives and management on projects on their mobile devices thanks to mobile features. It is possible to handle external communication and updates using stakeholder and customer relationship management software that is integrated with the ERP system. Another key benefit of ERP in construction is it enables remote access to all pertinent files and data. ERP systems assist in the efficient and speedy centralisation of huge amounts of data. Cloud applications can be used by the latest technology, which eliminates the need for big, expensive servers. ERP and BIM technologies provide more efficient project management and improved cost accuracy. All project data may be kept in a single repository, and numerous users can access it at once. Computing aided design applications can be integrated with BIM as a solution to improve efficiency in procurement in the construction industry.

3. METHODOLOGY

This review-based study applied the science mapping approach into the area of e-procurement in construction. It aims to provide insight into the existing challenges, benefits, and adoptions rates of e-procurement in the Australian construction industry and seeks to provide recommendations for future adoption. To achieve these objectives, a three-stage review process will be adopted.

3.1 Bibliometric search

The initial step of the review was the preliminary literature search using academic research database, Scopus. Scopus database has been used as the main source of information as it is considered a reliable source of scientific publications by academics (Baas et al., 2020). A comprehensive search was undertaken using a search string of keywords consisting of “e- procurement” or “procurement” or “sustainable procurement” or “digital procurement” and “construction” or “building”. Initially, 654 publications were found. These publications were further screened by only including publications dated between 2012 – 2022, journal articles exclusively and in English. This screening reduced the available literature samples to 492. Further screening of the remaining articles was conducted through the review of publication titles, abstracts, and keywords. Publications that were not closely related to this study were removed. This exercise highlighted that Automation in Construction, Construction Innovation and International Journal of Procurement Management had at least three papers each. A total of 82 papers from 45 journals were selected as the literature sample for the scientometric analysis.

3.2 Scientometric analysis

The second step of the review involved a scientometric analysis method by adopting the bibliometric mapping software VOSviewer (Van Eck and Waltman, 2010). Scientometrics can be described as the quantitative approach applied in text mining of scientific publications (Hawkins, cited in Aghimien et al., 2021). Scientometrics are useful in facilitating a visual perspective of structural and dynamic aspects of scientific research and analysis outlined within existing literature (Olawumi and Chan, cited in Aghimien et al., 2021). Thus, it has allowed researchers to discover existing systematic literature-related findings by connecting literature theories that may have been missed in manual review studies. VOSviewer generates, visualises, and analyses bibliometric networks (Van Eck and Waltman, 2010). Specifically, its text mining capabilities can construct network maps of journal sources, co-citations, co-authorship, country of origin and co-occurring keywords sourced from abstracts and bodies of research articles (Van Eck and Waltman, 2011). The literature sample sourced from Step 1 was imported into VOSviewer to create a network of co-occurrence keywords, along with lead journal authors and sources, and country of origin. The co-occurrence network assisted in identifying the primary area of interest of e-procurement.

4. RESULTS

A total of 30 countries was identified from the literature sample. Australia has the highest number of publications (15), with 82 citations. This is followed by United Kingdom with 9 publications and 86 citations, and China with 8 publications and 42 citations. Countries which closely followed included Malaysia, Hong Kong, and Nigeria. Interestingly, 14 out of the 30 countries only published one article between 2012 and 2022. The potential for further research within these countries to gain a greater understanding of e-procurement in construction could be beneficial for future researchers.

4.1 Publications per author

An authorship network map is used to identify the influential researchers in the e-procurement sector of construction research (Marzouk et al., 2022). A minimum of two published articles and five citations was set as the criteria of the authors. Tunji-Olayeni P., Yevu S.K., and Yu A.T.W. are the most productive scholars in this research domain based on the number of published articles. Additionally, Eadie, R., Perera, S., and Heaney, G., are in the same cluster, indicating their mutual relationship by citing one another’s work. The distance and connection lines between clusters can also be used to determine the authors linkage strength (Van Eck and Waltman, 2014). The quantitative measurements of the most prominent authors are explored in Table 1. The affiliation column shows the author’s institution at the time of publication and reveals that Ibem E.O. has the highest number of citations 79 for their three extracted documents. However, Yevu S.K., Yu A.T.W., and Tunji-Olayeni P. have the highest number of publications of four extracted documents with 14, 14 and 53 citations, respectively.

Table 1: Number of publications per author

Author	Affiliation	Nos	Citations
Tunji-Olayeni P.	Department of Building Technology, Covenant University, Nigeria	4	53
Yevu S.K.	Department of Building and Real Estate, The Hong Kong Polytechnic University, Kowloon, Hong Kong	4	14
Yu A.T.W.	Department of Building and Real Estate, The Hong Kong Polytechnic University, Kowloon, Hong Kong	4	14
Ibem E.O.	Department of Architecture, Covenant University, Nigeria	3	79
Layryea S.	School of Construction Economics and Management, University of Witwatersrand, South Africa	2	60
Grilo A.	UNIDEMI, Faculdade de Ciências e Tecnologia da, Universidade Nova de Lisboa, Monte de Caparica, Portugal	2	58
Costa A.A.	CIST/Instituto Superior Técnico, University of Lisbon, Portugal	2	37
Tavares L.V.	CESUR/Instituto Superior Técnico, University of Lisbon, Portugal	2	37

4.2 Publications per source

Publications within the literature sample originated from 49 sources. Table 2 depicts five sources with at least three publications focusing on e-procurement in construction. Engineering, Construction and Architectural Management and Construction Innovation have the highest number of extractions with four articles each and interestingly, 14 citations each. The most cited source is Automation in Construction, with three articles and 42 citations.

Table 2: Number of publications per source

Source	Nos	Citations
Engineering, Construction and Architectural Management	4	14
Construction Innovation	4	14
Automation in Construction	3	42
International Journal of Procurement Management	3	34
International Journal of Construction Management	3	22

4.3 Pattern of keywords

Through analysing keyword co-occurrences, knowledge advancements can be mapped to assist in understanding the knowledge structure of study (Su and Lee, 2010). To formulate such map, VOSviewer's co-occurrence analysis of keywords was used. The assessed articles produced a total of 459 keywords. VOSviewer groups the keywords into clusters using a set criterion for co-occurrences (Aghimien et al., 2021). The clusters identify common areas of research in past studies. The threshold of minimum number of occurrences of keywords in automatically set to five. According to Aghimien et at. (2021) there is no joint agreement regarding the ideal number of minimum co-occurrences to be applied in the body of knowledge. To ensure an optimal representation of keywords was identified in this study, the minimum number of occurrences was set to three. A total of 37 keywords met this threshold with a total link strength (TLS) of 460. General keywords such as "construction", "construction industry', "construction project", etc, were removed. Additionally, keywords with the same meaning, such as block-chain and blockchain were blended. Finally, 32 keywords were generated as illustrated in Fig. 1.

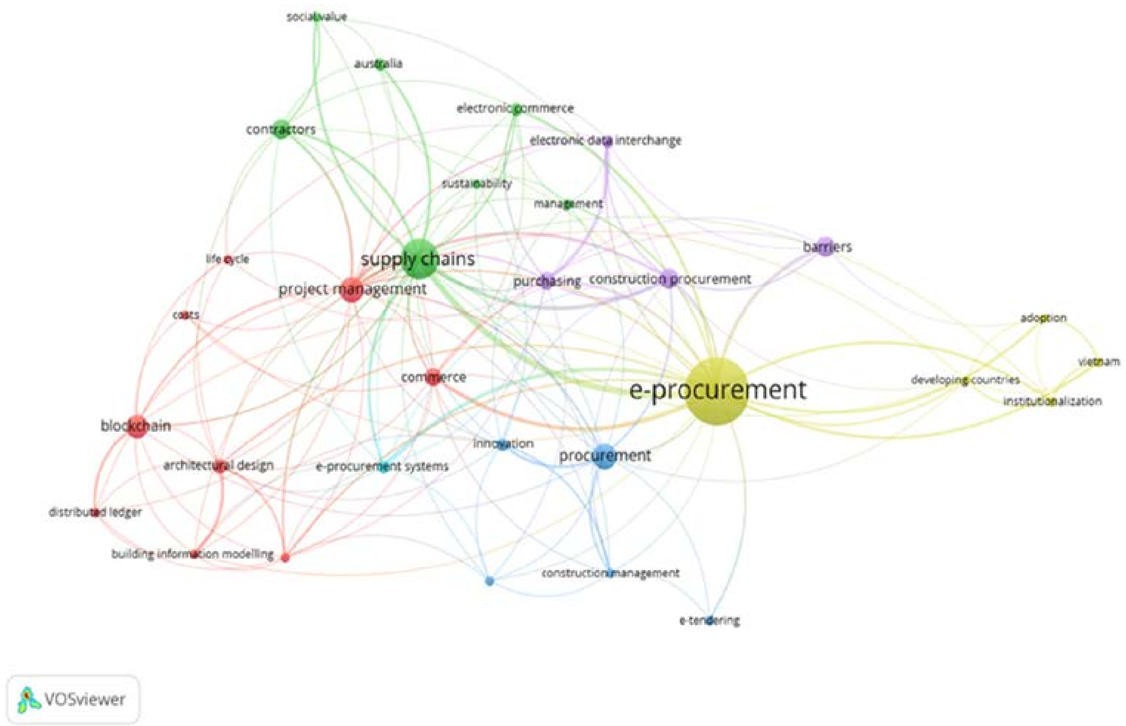

Fig. 1: Keyword co-occurrence network

The size of the nodes shows the frequency of occurrence and the lines between the nodes represent their co-occurrence in the same publication (Van Eck and Waltman, 2018). The closer the two nodes are, the greater the number of co-occurrences of the two keywords. For example, architectural design is found with close relationship with blockchain, information management and building information modelling design. It has been identified that, e-procurement, supply chains and project management were the most frequently entered keywords in the context of e- procurement in construction. It is unsurprising that e-procurement is at the centre of this network given it was the main search keyword to which other keywords are linked. Table 3 shows the occurrence and TLS of each keyword. Furthermore, the analysis categorised keywords that appeared multiple times into six clusters.

Table 3: List of clusters and co-occurring keywords

Cluster 1 (Red)	Occ.	TLS	***Cluster 3 (Blue)***	Occ.	TLS
Architectural design	5	16	Construction management	3	11
Blockchain	8	14	E-tendering	3	4
Building Information Modelling	3	11	Innovation	4	14
Commerce	6	18	Procurement	9	19
Costs	3	5	Public procurement	3	8
Life cycle	3	7	***Cluster 4 (Yellow)***		
Project management	9	34	Adoption	3	8
Cluster 2 (Green)			Developing countries	3	10
Australia	4	7	E-procurement	27	58
Contractors	7	15	Institutionalisation	3	9
Electronic commerce	4	13	Vietnam	3	8
Management	3	9	***Cluster 5 (Purple)***		
Social value	3	8	Barriers	7	10
Supply chains	15	47	Construction procurement	7	24
Sustainability	3	5	Electronic data interchange	4	15
			Purchasing	6	21
Occ. = Occurrence			***Cluster 6 (Teal)***		
TLS = Total Link Strength			E-procurement systems	4	16

4.4 Pattern of keywords

In addition to the network map, an overlay visualisation map is produced in VOSviewer. This map shows the keywords based on their year of publication during the period of 2016 to 2021. A coloured bar, identifying the years with a correlating colour is displayed in the bottom right- hand corner of the map (Van Eck and Waltman, 2018). For example, keywords coloured blue were published between 2016–2017 and focused on e-procurement areas relating to developing countries, adoption, institutionalisation, e-commerce, and information management. Publications between 2017–2019 seemed to shift focus slightly to areas such as supply chains, costs, barriers, purchasing, e-tendering, and e-procurement systems. These keywords are displayed in dark green/blue on the visualisation map. The latest years on the map which include 2020 – 2021 see a wide range of topics be introduced, including, electronic data exchange, social value, blockchain, building information modelling (BIM), innovation, sustainability, construction management and life cycle. These keywords are represented in bright green/yellow. Fig. 2 illustrates the overlay visualisation map. Examining the overlay visualisation map in conjunction with the

TLS results in Table 3 (cluster table) suggests that future research of e-procurement in construction could explore areas relating to e- tendering, costs, life cycle, sustainability, adoption, and social value. These areas have been identified to have low TLS results from past research studies. Despite their importance, these research areas have received little attention.

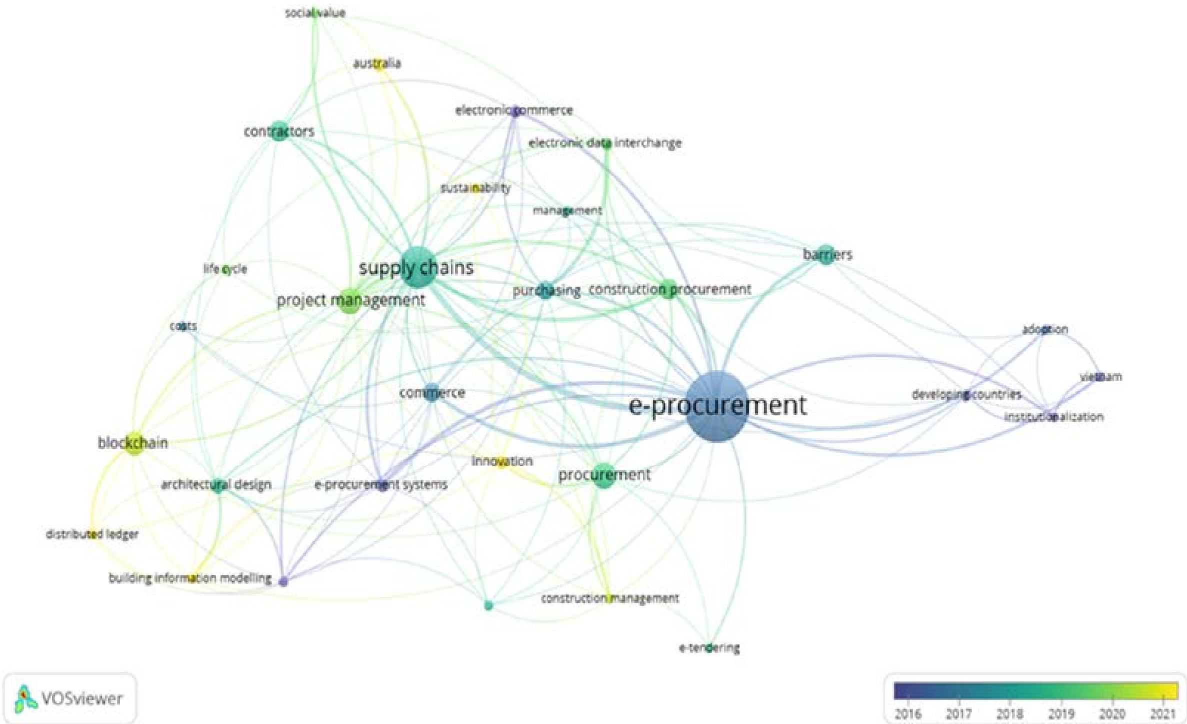

Fig. 2: Overlay visualization map.

5. DISCUSSION

From the foregoing review and bibliometric analysis, the following four key areas have been identified as the main categories of this research.

5.1 Adoption rates in other countries

Whilst several global studies into the barriers of e-procurement have been carried out (Yevu et al., 2022), analysis into the actual adoption levels of e-procurement practices globally is not heavily featured in the literature reviewed. Instead, analysis on adoption rates is often country specific. Several in-depth studies into a broad mix of developed and developing countries has been identified, such as Austria (Zunk et al., 2014), South Africa (Ibem and Laryea, 2015), Nigeria (Afolabi et al., 2019) and Vietnam (Tran et al., 2021). Whilst there has been some investigation into e-procurement practices in the Australian construction industry (Lin et al., 2022; Loosemore and Reid, 2019), there is very little contemporary literature into the adoption rates in the Australian context and how this compares globally. This Study will seek to partially address this gap in existing literature.

5.2 Benefits and enablers of e-procurement

There is a significant volume of research and analysis into the benefits and enablers of e- procurement practices. The drivers and barriers of e-procurement in the construction sector was comprehensively examined in Eadie et al. (2010), with the key drivers identified including (1) Process, transaction and administration cost savings; (2) Convenience of archiving completed work; (3) Increased quality, efficiency and accuracy; and (4) Shortened internal and external communication cycle times. The literature into drivers and benefits has continually strengthened over the past decade, with key contributions from Yevu et al., (2021), Khahro et al., (2021), Pattanayak and Punyatoya (2021) and Wimalasena and Gunatilake (2018), amongst others.

Despite the significant volume of literature, there are few examples of 'firm-level' studies which validate the perceived benefits of e-procurement from a construction organisation perspective. The need for more firm-level studies to measure the link between productivity and digitization in the context of the Australian construction industry was identified by Leviakangas et al., (2017). There is also a clear lack of Australian-focused literature which examines the potential benefits of e-procurement based on the local industry environment.

5.3 Barriers to e-procurement adoption and challenges upon implementation

As observed with benefits and enablers, there is an extensive volume of existing literature and research into the barriers to e-procurement adoption in the construction industry. Eadie et al. (2010, 2012) was one of the first to examine these barriers in significant detail, though extensive primary research has been carried out across multiple countries since that time, with prominent examples being Yevu et al., (2021), Yevu and Yu (2019), Nawi et al., (2017) and Afolabi et al., (2017). Yevu et. al (2021) categorised some 21 individual barriers to e-procurement adoption into six barrier groups based on an extensive review of existing literature and primary research. These barrier groups include:

i. Technological Usability and Evolution-Related Barriers

ii. Security and Unsupportive Environment-Related Barriers

iii. Culture-Related Barriers

iv. Infrastructure-Related Barriers

v. Unethical Practices–Related Barriers.

vi. Financial and Skill-Related Barriers

There is more limited research into the challenges of e-procurement usage in the construction industry upon implementation. Primary research through direct interviews with construction industry professionals in Ibem et al. (2021), Isikdag (2019) Nawi et al. (2017) and Brandon- Jones (2017) provide useful insights into the first-hand challenges of industry participants upon implementation of e-procurement systems. Whilst there is an excellent base of research from which the Study can leverage, it is evident from the literature review that there is a lack of Australian-focused studies which have identified (if any) Australian-specific barriers and challenges of e-procurement practices in the construction sector. The Study will seek to examine this in detail and further build upon the strong evidence base of research into the barriers of e-procurement adoption and the challenges identified by industry participants upon implementation of e-procurement systems.

5.4 Conclusions

Existing literature has carried out extensive engagement with industry stakeholders to identify the barriers to adopting e-procurement practices and the challenges upon their implementation as observed in Ibem et al., (2021), Isikdag (2019) Nawi et al. (2017) and Brandon-Jones (2017). It is noted that none of these studies have focused specifically on the Australian construction industry. Whilst there is an excellent base of research from which this study can leverage, it is evident from the literature review that there is a lack of Australian-focused studies on specific barriers and challenges of e-procurement practices in the construction sector. The scope of this review focusses on the implementation of e-procurement in facilitating towards digital transformation in the construction sector. The study examines this in detail in the next phase of study and further build upon the strong evidence base of research into the barriers of e-procurement adoption and the challenges identified by industry participants upon implementation of e-procurement systems. Study findings may be used to guide construction companies' investment choices in digitally modernising the procurement function. Through their procurement processes, organisations may boost their digital transformation objectives.

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A PRELIMINARY INVESTIGATION OF KNOWLEDGE MANAGEMENT TOOLS FOR THE CONSTRUCTION SECTOR

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ABSTRACT: *Knowledge management (KM) is used by construction firms to establish organizational memory (OM) and consequently improve their performance by learning from past mistakes and best practices. Knowledge is the input to innovation; thus, the industry must adopt better ways of managing knowledge for advancement in the construction processes. Knowledge management consists of locating, modifying, and sharing knowledge to meet the needs of the current fast-paced sector. Various tools have been developed to support KM and OM in construction companies, however, it is very important to adequately address the needs of the sector for successful implementations. The aim of this study is to analyze the existing KM tools and evaluate their compatibility with the necessities of today's sector. First, knowledge types in the construction industry were outlined, and existing KM tools were evaluated. Then, expert interviews were performed with two representatives from a prominent construction and a prominent consulting firm to delineate the contemporaneous KM practices as well as the KM needs in the construction industry. Finally, current practice in KM in the construction sector is evaluated, and a vision is developed for a more effective KM approach that could support OM in construction firms.*

KEYWORDS: *Knowledge Management, Organizational Memory, Construction Firms, Software Tools*

1. INTRODUCTION

Intellectual assets are the primary capital in knowledge-intensive industries. For companies looking to thrive in knowledge-based work environments, in-house procedures should be created to accumulate, explore, and exploit corporate and individual knowledge. The term "knowledge management (KM)" was used in Western countries for the first time during the late 20th century in books, academic research, consulting, and organizational adaptation processes. Nevertheless, the management of organizational knowledge did not truly start until the mid-1990s. Implementations of KM mechanisms were somehow present in companies long before these concepts emerged, such as knowledge-sharing activities. In the early 1990s, sector leaders such as BP, Shell, and Chevron used KM initiatives before any academic publication (Quintas, 2005). This shows that KM techniques were naturally used as a part of cooperative incentives to gain a competitive advantage and improve business performance. Today, KM is at the center of any modern business as rapid developments in information and communication technologies influence a profound shift from tangible assets to intangible assets focusing on people and knowledge. Even though many sectors with such needs have adapted ways of managing knowledge today, it is only in the last ten years that companies in the construction sector have started familiarizing themselves with the KM concept (Rezgui & Miles, 2011).

In order to benefit from KM as a pursuit of enriching organizational memory (OM) and achieving productivity, the types of knowledge encountered must be analyzed. There is a popular attempt to categorize types of knowledge in order to ease comprehending, storing, and sharing it. Each categorization considers different aspects of knowledge that guide the analysis in the specific field. The most applicable and renowned categorization for the knowledge management field belongs to Polanyi (Polanyi, 1966), which divides knowledge into tacit and explicit knowledge. Explicit knowledge is the recordable or documented information that can be written, coded, or saved with the intention to transmit knowledge. Tacit knowledge is the knowledge an individual owns, gathered from their insights, personal experience, and observations.

The construction sector is a knowledge-based industry comprising different project participants such as designers, engineers, contractors, and clients that generate overwhelming amounts of data in each project. Effective KM is crucial to organize and benefit from this data overflow. In the past decade, much research has focused on KM for various other sectors, such as consulting, finance, or computer science. Despite the evident need, the construction sector is still lacking effective KM tools to foster organizational memory in a project-based environment. The aim of this study is to explore the KM tools used for gathering, sharing, and storing tacit and explicit knowledge in construction companies. Since KM is effectively used in only a few initiator companies, the authors investigated the steps taken by these pioneers to delineate KM best practices for the construction sector.

This paper reports the results of the two pilot interviews done with the senior managers of two multinational firms.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Bartu Kologlu, Deniz Artan, *A Preliminary Investigation of Knowledge Management Tools for the Construction Sector,* pp. 499-507, © 2023 Author(s),
CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.48

The first firm is a consulting firm operating in 50 countries with more than 55 years of experience in the consulting sector. The interview was performed with a senior project director who has 10 years of experience in the sector. The second firm was chosen among the few contractors that use KM effectively, which operates in 50 countries with 107 years of experience in the construction sector. They are among the sector leaders with more than 80,000 employees. The interview was performed with a country manager who has 20 years of experience in the sector. Both experts were asked the same set of 12 questions under three main categories, which were: Data Collection, Data Accessibility and Usage, and Knowledge Management (See Appendix for the Questionnaire Form). The interviews with the company representatives took approximately one and a half hours each, during which the experts were guided by the questions and expressed their views on the topics driven from, but not limited to, the questionnaire.

2. EXPLICIT & TACIT KNOWLEDGE

Resources and competencies are critical factors for companies to survive in an evolving and fiercely competitive atmosphere in the knowledge-based economy (Subramaniam & Youndt, 2005). Thus, one of the biggest challenges is to be able to distinguish characteristics of knowledge from information. Knowledge can be either explicit or tacit. It is also important to distinguish tacit and explicit knowledge in order to comprehend the notion of organizational knowledge

Explicit knowledge is founded on widely recognized and objective standards. It is archived in the form of written procedures or documents. Therefore, it can be codified and communicated with relative ease. It encompasses the majority of knowledge exchange inside companies. Since explicit knowledge can be easily documented, formalized, and expressed, processes of sharing knowledge tend to be more widely used in the workplace. Several management tools are used to increase the willingness of employees to share their explicit knowledge, such as handbooks and information technology systems (Coakes, 2006). Since this knowledge can be codified, it may be reused repeatedly and is, hence, simpler to convey. Design codes of practice, performance requirements, paper-based or electronic drawings, and building methods are a few examples of explicit knowledge in the construction industry (Charles & Robinson, 2011). Other instances of explicit information include design sketches and photographs, 3-D models, and textbooks. Explicit knowledge is the data that can be interpreted by others once it has been codified. People with supplementary knowledge who are able to understand the "codes" and derive meaning from them may be able to understand the presented knowledge. Even this process of comprehending or deriving meaning from knowledge requires the application of implicit interpretational, evaluative, and generalizing skills.

The foundation of tacit knowledge sharing is human experience (Nonaka & Takeuchi, 1995). Polanyi (1966) described tacit knowledge as instinctive knowledge that cannot be expressed coherently by means of words; it is acquired via collective involvement and can be challenging to describe, systematize, and transmit. The informal adoption of taught behavior and methods obtains the uncodified and disembodied know-how. Furthermore, tacit knowledge cannot be directly conveyed to someone since knowledge and task performance have distinctive personal qualities, requiring the acquirer to adjust their mindset. Hence, the degree to which it is conveyed varies. Tacit knowledge can be maintained by individuals or as a team in the form of collective experiences and assessments of events. Employee objectives, capabilities, routines, and intangible information are sources of individual tacit knowledge. On the other hand, collective tacit knowledge may arise from various notions, including top management strategies, organizational agreement on previous shared experiences, company procedures, company culture, and professional customs (Lyles & Schwenk, 1992). Tacit knowledge can also be described as knowledge that has been converted into a habit and possesses a personal quality, as well as being very context-specific. The reality of tacit knowledge is that the less clear and codified the tacit know-how, the more difficult it is for individuals and businesses to internalize. Academics and managers have overlooked the notion of tacit knowledge until recently, although it now plays a major role in corporate growth and economic competitiveness (Howells, 1996). Transmitting tacit knowledge is frequently done primarily through direct conversation. Some tacit knowledge transfers are official as a result of training programs or seminars, while others are more informal as a consequence of interdepartmental work teams, unofficial social networks, and personnel interactions. The desire and ability of individuals to share their knowledge and apply it in practice are crucial to the formal and informal transmission of tacit knowledge (Holste & Fields, 2010). On the other hand, explicit knowledge is able to be formalized and communicated through structured and methodical means, such as in the form of rules and procedures (Nonaka & Takeuchi, 1995).

The difference between individual and collective explicit knowledge is that individual explicit knowledge consists of expertise and abilities that are easily teachable or writable, whereas collective explicit knowledge lies in standard operating procedures, record keeping, IT systems, and policies (Brown & Duguid, 1991). Regarding innovation speed and financial success, tacit knowledge sharing is more influential than explicit knowledge sharing, whereas innovation quality and operational efficiency are influenced more by explicit knowledge sharing (Wang &Wang, 2012). Thus, companies must learn to share and store both knowledge practices to unlock their potential benefits fully. The following statement explains the criticality of harmonizing explicit knowledge with tacit knowledge; *"If Nasa wanted to go to the moon again, it would have to start from scratch, having lost not the data, but the human expertise that took it there last time"* (Brown & Duguid, 2000,p.122).

3. KNOWLEDGE MANAGEMENT

In a knowledge economy, conducting business has opportunities as well as drawbacks. The opportunities include the potential for expanding market share, enhancing productivity, and increasing profitability through innovation and efficient knowledge asset management. The key difficulties are dealing with rising global competitiveness, shifting levels and patterns of client, customer, and societal demands, and the speed as well as effects of change in information and communication technologies (ICT) (Charles & Robinson, 2011). In order to gain a competitive edge, one must be able to use knowledge efficiently. A common question is whether organizations store knowledge in memory similarly to how people do. The answer is that there is a rising notion that organizations do have frameworks, practices, structures, and other tangible artifacts that demonstrate the existence of knowledge encoded in the organizational culture.

The formation of an organizational memory (OM) within an organization is a critical knowledge management activity that promotes the organizational learning (OL) processes (Ozorhon, Dikmen & Birgonul, 2005). OM can be defined as the means by which knowledge from the past is brought to bear on present activities; thus, it helps to learn from previous experiences (Stein & Zwass, 1995). OM becomes a corporate asset by sharing, organizing, storing, and reusing the knowledge created previously. The knowledge management activities within organizations should aim to enhance the OM.

OM requires continuous improvement and growth of organizational knowledge, which means that both the organizations and the individuals within them must be constant learners. One important aspect of KM is its need to reinvent your organization through learning constantly. Experience-based knowledge is incorporated into procedures and is embedded in technologies and systems. Organizational routines and a culture that encourages the creation, assimilation, and abandonment of outdated information and practices must be developed in order to promote continuous change. Organizations must accomplish two goals that may be in conflict with one another: first, they must build their knowledge bases over time and draw lessons from their past experiences; second, they must make sure that they are learning outside of their core competencies and develop the capacity to assimilate new knowledge in order to be able to respond to change (Quintas, 2005). The generation of knowledge is frequently seen as somehow more significant than knowledge reuse, more challenging to manage, and less dependent on information technology support. However, perhaps a more common organizational concern—and one that is unmistakably tied to organizational effectiveness—is the efficient reuse of knowledge (Markus, 2001). The reuse of knowledge in various decision-making mechanisms and circumstances is expected to result in the generation of new remarks that automatically update the organizational memory when stored back into the system. A cycle should be made where organizational memory is referred to on knowledge transactions, and outcomes are reflected back to enhance the organizational memory.

Construction companies must implement knowledge management mechanisms in their daily routines to improve effectiveness and thrive in an overly competitive sector. In order to meet this objective, first, the sources of knowledge generation need to be analyzed, as well as the type of knowledge they generate. As explained in the previous section, the possible tools for regulating and sharing tacit and explicit knowledge differ due to the nature of the knowledge.

4. KNOWLEDGE MANAGEMENT TOOLS

There are a variety of knowledge management tools available to choose from thus, it is vital to select the appropriate tool that addresses the goals of the organization adequately. The KM tools can be categorized as IT and non-IT-based tools that are used to support the essential aspects of KM such as sharing, reusing, and locating knowledge. In order to distinguish between the two categories, experts suggest naming IT-based tools as KM technologies and non-IT-based as KM techniques (Al-Ghassani, Anumba, Carrillo, & Robinson, 2005).

KM techniques do not require IT tools to execute the sub-processes of KM, such as knowledge sharing. It is clear that the scope and nature of human knowledge are much broader than what can be encoded by IT tools. Some of these tools are; seminars, post-project reviews, communes of practice, project feedback mechanisms, mentor programs, and training programs. Knowledge has a social aspect thus, seminars, communes of practice (where different professions meet to interact), and training programs are great opportunities for employees from different backgrounds to meet and share knowledge. Whereas post-project reviews, project feedback mechanisms, and mentor programs promise a similar scenario to a master-apprentice model where junior individuals get to be criticized and influenced directly by a senior colleague, which is an extremely effective knowledge-sharing mechanism. These tools may seem simpler to implement when compared to IT-based KM tools, however, they hold a much greater value for the initialization of tacit knowledge when compared to IT-based tools. Often the highly skilled members of the working environment are unaware of their tacit knowledge, such as their problem-solving skills or the resources they use. For this reason, knowledge sharing becomes highly dependent on communication within the working environment. Tacit knowledge is personal, linked to experience and learning, and cannot be coded. This results in tacit knowledge being shared within groups with common learning experiences and understandings rooted in common practice via non-codified pathways (Brown & Duguid, 1998).

The IT-based KM tools mainly focus on capturing codifiable knowledge. These tools act as a great OM archive that eases how organizations create an organizational learning and knowledge management culture. The data stored in software and hardware systems can be referred to and reused whenever necessary, making monitoring the data much simpler. Today, there is a variety of software-based programs on the market that offer diversified approaches to KM.

Using Artificial Intelligence (AI) and Machine Learning (ML) based software for KM is one of the leading trends in the knowledge industry. The classification, labeling, and retrieval of data are only a few examples of knowledge management tasks that can automated with the help of AI. Large volumes of unstructured data may be analyzed by these technologies, making it simpler to find insightful patterns and trends in a company's knowledge base. According to Forrester Consulting's principal analyst, Gualtieri (2016), between 60% to 73% of all the collected data within an enterprise goes unused for analytics. With the help of AI-driven KM tools, advanced data structuring could be done for an insight-driven data presentation for the knowledge seeker. The outcome is similar to a personal intelligent assistant that can revolutionize how knowledge workers consume meaningful information and increase their cognitive capacity by providing them with more efficient tools for processing, filtering, sorting, and navigating information sources (Jarrahi, Askay, Eshraghi & Smith, 2022). Thus, organizations can improve their search capabilities, use time more efficiently for knowledge management operations, and provide employees with more individualized content suggestions by implementing AI-powered algorithms.

Another current KM-IT tool is the ontology-based KM system and its application. A knowledge management system based on an ontology is more capable of encouraging the integration of linked resources, identifying precise knowledge rapidly, and steering away a significant amount of unnecessary knowledge. The procedure transforms disorganized knowledge data into structured knowledge by transferring all the necessary information. Storage of knowledge is the process by which the metadata is extracted from the knowledge sources acquired, and knowledge objects are marked in the implication of ontology and metadata standards, with the aim of transforming semi-structured and unstructured knowledge into structured knowledge and storing it in the knowledge base (Zhang, Zhao, Wie & Chen, 2015).

Whether it is a more futuristic approach to KM, such as AI-based tools or more simple cloud-based archive programs, these IT tools share distinct key functions to cover the majority of the needs of KM. Firstly, a "Document Management" function must be present to act as an archive with a correct taxonomy for material and track document changes when they occur. The second one is a "Knowledge Archive". Knowledge bases store structured and unstructured information in the system. These could be not only documents but also tutorials, videos, etc. The third key functionality is the "Security System". This feature limits accessibility for predetermined employees that determines which data is available to obtain. The fourth feature is a strong "Search Function". This function aims to save time when searching for past documents. The final feature should be "Communication Tools". Communication channels can make the systems much more efficient, especially when one has further questions on the uploaded material and can directly reach the author.

5. CONSTRUCTION SECTOR & KM

The activities of today's construction industry demand an increased level of knowledge, skills, and learning, as the sector is a multilayered knowledge-based environment that has knowledge input from different project parties

(Ferrada, Núñez, Neyem, Serpell, & Sepúlveda, 2016). Explicit and tacit knowledge come together to form organizational knowledge. In every individual's thought lies an accumulation of tacit knowledge. It is a collection of experiences, observations, and intuition that can be either cognitive or technical. Examples of tacit knowledge in the context of construction may include estimating and tendering prices that have been prepared over time through practical experience in preparing bids, encountering the construction processes, interaction with clients/customers and project team members in the construction supply chain, as well as an understanding of markets. Experience-based, judgmental, and context-specific knowledge makes it challenging to codify and share this type of knowledge.

Explicit knowledge in construction is generally the data obtained from site activities. This could be man-hours, machine hours, periodical reports, unit prices, and anything generated from real-life implementations. As a result, better ways of knowledge management should be the primary target to comprehend the overflow of data in the construction sector. However, this might be unfavorable at first for some managers due to the general nature of the lack of human resources or timely pressure on on-site activities. Thus, the general outcome and long-term benefits of adopting such an ideology must be made clear to decision-makers for the right resource allocation. Every employee in a construction organization must embrace a culture that values knowledge capture and sharing of knowledge.

However, there are a set of socio-technical barriers defined by Rezgui & Miles (2011) that limit the progress of KM in the construction industry. Firstly, employees do not perceive any immediate benefits from sharing knowledge and experiences. In fact, this is seen as a possible threat to their status as "experts" since there is usually no encouragement for a supportive knowledge-sharing culture focused on all employees. (e.g., by implementing creative ways for rewards and recognition). Next, shelf solutions do not work, and there is a weak culture of software adoption. In order to perform their duties and access software, employees are frequently limited to a specific place, which is usually their office. However, access to information from construction sites is frequently constrained by network availability. Another obstacle is that the industry is divided and organized into numerous disciplines, each of which has its own rules and specialized terminology. There is not a particular language that captures a shared comprehension of construction principles utilized across disciplines. All these aforementioned challenges limit effective communication and the sharing of experiences.

By actively participating in projects over an extended length of time, one can gain valuable construction knowledge. However, this is usually not the case, as employee turnover is radically high. The specific needs of the employees who will use the project data may not always be understood by those in charge of gathering and archiving it. Furthermore, data is gathered and archived at the end of the construction phase rather than being handled while it is being created. By now, it is likely that those who were aware of the project have moved on to other projects. Again, due to high turnover, many businesses keep archives projects however, it is challenging to get in touch with the original report authors. These projects should be available to be used with little (or no) consultation, this past data should have a rich representation of the data context. Lastly, decision-making objectives are frequently not noted or documented. The millions of spontaneous messages, phone calls, emails, and discussions that comprise much project-related information require complex methods to track and document.

In order to understand the reflections of these limitations on current construction sector knowledge management practices, two interviews were conducted. The first interview is held with the country manager of a 100-year-old multi-national construction firm, which is among the top 20 highest-grossing international contractors according to ENR magazine 2023. The second interview is made with a senior consultant in one of the top global strategy consultancy firms by revenue, who has one of her expertise in KM. The reason for the second interview being made with a representative from the consultancy sector is due to the factor that they were one of the earliest adaptors of KM tools in their organizations. From the early stages of the introduction of the KM concept, the major consulting firms took advantage of the immense potential of information technology as the driving force in the business world. The ideology has always been similar to the one today, which combines well-known IT tools like databases to make it easier to gather, share, store, retrieve, and use knowledge (Easterby-Smith & Lyles, 2015). For this reason, comparing the approaches to KM of a successful construction firm to one of the best knowledge-managing sectors in business would outline the necessities to be implemented by the construction industry, which is the aim of this study.

6. FINDINGS OF THE EXPERT INTERVIEWS

The interview questions were categorized under three headlines: Data Collection, Data Accessibility/ Usage and Updates, and Knowledge Management. The results are explained with the participants being referred to as

"Consultancy (Firm) Representative" and "Construction (Firm) Representative". On the first question of the Data Collection section, participants were asked if there is a department in their organization dedicated to collecting and storing data from past projects. It was revealed by the construction representative that there was no such dedicated department, but all the departments in the headquarters (such as Procurement, Legal Matters, HR, etc.) would collect their own data from the sites. The consultancy representative revealed that they did have a special team dedicated to knowledge management for every specific field of activity. Next, participants were asked if their organizations had a digital database and a predetermined taxonomy for storing this data and what type of data was chosen to be stored in this system. The construction representative explained that they do have a digital database to store this knowledge, but only the specific departments have a taxonomy to obtain worldwide uniformity, such as the finance department, cost control department, and HSEQ department. It was added that they try and store most of the explicit data generated from the site, such as the man-hours, machine hours, accident rates, etc. Similarly, the consultancy representative stated that they do have a company-wide digital database to store project data. It was revealed that the uploaded material usually is in project analysis reports that have some identifiers that make it easy to find it in the future, such as keywords, date, location of the project, project team, a summary page, etc.

The next section was about Data Accessibility/Usage and Updates, where the first question inquired if the stored data from the previous projects could be accessible anytime when needed and who could access this data. The construction representative stated that this data is only accessible to the related departments at the headquarters, and site employees could only access it via headquarters. On the other hand, the consultant representative made clear that this data could be accessible to anyone at any time. The second question on this topic examined if the ongoing projects referred to the stored data, how often they referred to it, and what type of data was most frequently requested. The answers to this question were quite different, as the construction representative stated that even though there are times when the site refers to the stored data, it is not too regularly requested. He added that the most requested data from the headquarters is the sub-contractor-related data (such as their prices, if they have worked with them before, and their references). On the contrary, the consultant representative stated that it is referred to at the beginning of each project. The last question was asked to determine how frequently the system was updated with the knowledge currently produced. The construction representative stated that it was every month unless there was a special reason to make it more frequent, and the consultancy representative stated that the sanitized version (a version that prevents the disclosure of the client) was uploaded at the end of each project.

The final section consisted of questions regarding the KM policies. The first question of this section was to determine the explicit knowledge-sharing methods used in their company. The construction representative stated that they have an e-learning platform for employees to work on themselves and that some of the end project reports and analyses are available for every employee to view. The major explicit knowledge sharing on the consulting firm is stated to be their online tool, where the majority of the project data is imported into. The last question was about the knowledge-sharing mechanisms of tacit knowledge. The construction representative stated that there are regular voluntary webinars and seminars made, but most employees are expected to obtain this knowledge from working with one another, similar to the master-apprentice model. The consultant representative stated that they too, have seminars on general business matters and seminars on expertise fields. However, it was explained that although these seminars are voluntary, they have a reward system, such as being awarded a certificate or conference invitation. Additionally, it was explained that they, too aim to convey the tacit knowledge by the mater-apprentice model but in a more structured way. Firstly, a pairing system is used within project groups where seniors and juniors are matched. Next, throughout a project, the juniors get to work with their seniors to understand the business approaches they take in action. Then, after the end of the project, there is a feedback mechanism that monitors the desired performance of individuals, which is a great way to restructure the knowledge learned from the project.

7. DISCUSSION AND CONCLUSION

The review performed on the requirements of the construction sector revealed that knowledge management tools need to (1) collect the contextual details in a structured, continuous and real-time manner, (2) overcome difficulties in the extraction of knowledge from text-based data, (3) encourage a knowledge sharing culture, (4) combat the limits of the fragmented industry in effective communication and the sharing of experiences, (5) meet the specific needs of the employees who will use the project data, not those in charge of gathering and archiving it, and (6) facilitate efficient reuse of knowledge and learning outside of core competencies.

The findings from the expert interview show similarities as well as major differences. For example, even though each department is set to collect data from the site in the construction firm, it is ambiguous how much the employees are involved in the real site activity when compared to knowledge management teams in consulting firms who act as part of the project for a period of time. Another major difference is seen with the KM software these companies use. The accessibility and usability of the KM tool of the construction firm seem considerably constrained in terms of creating a knowledge-sharing culture compared to the KM tool used in the consulting firm. Even though the diversity of data is richer in construction, due to a lack of accessibility from key players and site personnel, there are significant limits to embracing the concept as a company culture. Finally, the biggest gap between their KM ideologies is related to their approach to sharing tacit knowledge. We can see a clear company culture inside the consultancy firm that motivates and provokes both the knowledge owner and knowledge seeker to interact in a knowledge-sharing activity. This is either done by rewarding systems for participation in seminars or compulsory feedback mechanisms post-project. On the other hand, an environment is set for this knowledge-sharing interaction in the construction firm, however, it is left to the employee will and enthusiasm to engage in it.

The interview results reveal that most of the determined KM requirements of the construction industry have not been incorporated into the current tools and practices. Whether it is due to the natural barriers of the construction firms, which is explained in the previous section, or being the latecomer to the KM concept, one thing is for sure; which is that are many areas of improvement for enhancing the engagement in KM within the construction firms. The sector has a huge advantage in generating enormous amounts of knowledge, which, if and when interpreted correctly, could result in a much more efficient, resilient, and technologically advanced sector.

These challenges faced by construction companies can only be overcome by establishing and maintaining a knowledge culture where knowledge is valued and generated, shared, and utilized as an instinctive aspect of corporate activities. Organizations and the individuals within them must be constant learners, and this demands a clear vision, strong leadership, and solid processes from the corporation. If the construction industry is to build and maintain the capability in a knowledge economy, it must shift its adversarial culture to a sharing culture. Furthermore, it has to learn from each project and then transfer knowledge from projects to organizational bases to improve OM. A cycle should be made where organizational memory is referred to on knowledge transactions, and outcomes are reflected back to enhance the organizational memory. For future studies, this research that acts as a pilot study will be broadened with more interviews from the construction sector to understand the in-depth usage of KM tools within organizations.

ACKNOWLEDGMENTS

This thesis is based on Bartu Koloğlu's MSc. Thesis. We appreciate the significant contributions of all experts to the completion of this paper.

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8. APPENDIX: QUESTIONNAIRE FORM

This questionnaire form is part of the MSc thesis study of Bartu Kologlu at Istanbul Technical University Construction Management Program. The aim of the thesis is to understand the current knowledge management practices and the tools that construction companies use to maintain and enhance their organizational memory. The answers will only be used for academic purposes, and the answers will be evaluated anonymously without the identity of the participant/organization.

1) Data Collection: One of the main capital of knowledge-intensive sectors such as construction/consulting is intellectual assets. Most of the processes are generated toward exploration, accumulation, and exploitation of individual and firm knowledge. Your company has been in the construction/consulting sector for many years and has completed many projects.
   1.1) Is there a department/process in your company that collects and stores the knowledge data acquired from

the projects?

1.2) What kind of data is collected/stored from the previous projects (financials, man-hours, machine hours, financials, reports, etc.)?

1.3) How often is this data collected?

1.4) How is this data stored? Is there a digital database for this purpose? If yes, is there a predetermined taxonomy or a uniform filing system that is used to store the data?

2) Data Accessibility and Usage

2.1) Is the stored data from the previous projects accessible when needed?

2.2) If yes, do the ongoing projects use this data? How often is the previous data used for ongoing projects?

2.3) What type of data is used? Please list the specific information/data items used most frequently.

2.4) Is there an IT program to access this data? If yes, what is the most critical aspect of this program to operate correctly?

3) Knowledge Management: We can divide knowledge into two categories: Explicit and Tacit. Explicit Knowledge is the documented or recorded information that is written or saved. Tacit knowledge is the knowledge that an individual owns that is gathered from their personal experience, insights, and observations.

3.1) What are the knowledge-sharing methods in your company for explicit knowledge (seminars, shared monthly reports, etc.)?

3.2) Skilled members of a community of practitioners are often unaware of the tacit knowledge they possess, e.g., their problem recognition and problem-solving behavior, the rules that they follow, and the knowledge sources that they draw on. What are the methods in your company that convey tacit knowledge transactions?

3.3) The sector operates in a project-based environment. How can you ensure that individual knowledge becomes a company asset and does not disappear when that person is no longer part of the company?

3.4) Are there any other Organizational Learning practices your company performs?

IMPROVING BIM AUTHORING PROCESS REPRODUCIBILITY WITH ENHANCED BIM LOGGING

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ABSTRACT: *This paper presents an enhanced BIM logger designed to capture both geometry and attribute changes of building element geometries, thereby offering a transparent source of representation of the BIM authoring process. The authors developed the logger and reproduction algorithm using the Revit C# API based on the analysis of information required to define building elements and associated attributes. The enhanced BIM log was evaluated through a case study of Villa Savoye designed by Le Corbusier. Despite negligible discrepancies, the results show that the enhanced BIM log can accurately represent the BIM authoring process capturing and reproducing 92.45% of the building elements from the original BIM model. Future research can focus on expanding the scope of logging and probing the potential of automating the BIM authoring process using these enhanced BIM logs.*

KEYWORDS: *Building information modeling (BIM), BIM log mining, BIM authoring software, Custom BIM log, Authoring process reproducibility.*

1. INTRODUCTION

The architecture, engineering, construction, and operation (AECO) industry has experienced a transformational shift with the widespread adoption of BIM technology. The shift has not only enhanced productivity but also improved informed decision-making within the sector (Sacks et al., 2018). Although BIM models—products of the BIM process—display the finalized decisions of a project, they encapsulate a wealth of insights due to the extensive decision-making endeavors underpinning their authoring. Consequently, the BIM authoring process can serve as a valuable knowledge repository for understanding the decision-making process.

BIM log mining seeks to extract these insights by examining the BIM logs in detail. BIM logs serve as invaluable data reservoirs, capturing sequential events recorded during BIM software usage (Jang et al., 2023). Previous studies have explored various aspects of the BIM authoring process, from design authoring patterns (Yarmohammadi et al., 2017), productivity (Shin, 2023; Shin et al., 2022), and collaboration patterns (Zhang & Ashuri, 2018), to the specific roles of modelers (Forcael et al., 2020).

Researchers have emphasized the significance of incorporating data attributes to elucidate the as-happened process within the log to attain reliable results from the analysis (Bose et al., 2013; Suriadi et al., 2017). Nonetheless, the BIM logs produced by prevailing BIM software overlook modifications in building elements undertaken during the BIM authoring phase because they were originally developed for maintenance operations (Autodesk, 2022). Consequently, such logs often miss the depth required to accurately capture the BIM authoring narrative (Jang et al., 2023; Yarmohammadi & Castro-Lacouture, 2018). Even though efforts have been made to enhance these logs through custom loggers (Gao et al., 2021; Jang et al., 2021; Kouhestani & Nik-Bakht, 2020; Pan & Zhang, 2021; Yarmohammadi & Castro-Lacouture, 2018), these adaptations still are not able to capture critical geometric nuances like shapes, scales, and locations—details pivotal to understanding the evolution and decision making involved in the BIM authorship.

To address the issue, this paper introduces an improved BIM logger capable of capturing comprehensive details for the precise replication of the BIM authoring process. The methodology behind this advanced logger includes analyzing the essential data needed to describe building elements in Autodesk Revit, followed by the design of a custom BIM logger to record this crucial information. In addition, a reproduction algorithm was developed to evaluate the logger's accuracy in representing the BIM authoring process. The reproducibility of the logger was further validated through a case study.

The paper is structured as follows. Section 2 reviews previous custom BIM loggers proposed in the literature, and Section 3 describes the research methodology employed in this study. Section 4 reviews the minimum information

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Suhyung Jang, Ghang Lee, *Improving BIM Authoring Process Reproducibility with Enhanced BIM Logging,* pp. 508-514, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.49

requirements to define BIM elements in Revit, and Section 5 outlines the development of the enhanced BIM logger and reproduction algorithm. Section 6 evaluates the reproducibility of the enhanced BIM logger through a case study, and Section 7 concludes the paper.

2. LITERATURE REVIEW

BIM log mining is a data analysis approach that utilizes process mining techniques to explore BIM event logs collected during a BIM software operation. Process mining includes various techniques for automated process discovery, social network analysis, process optimization, case prediction, and history-based recommendations (Aalst et al., 2011). However, event log imperfections can lead to unreliable results, and researchers have introduced an incremental approach to evaluating event log fitness and a methodology to guide process mining execution (Bose et al., 2013; Suriadi et al., 2017).

While improving event log quality has received significant attention, several studies have focused on enhancing the information included in the BIM logs. These include custom Revit logger which extracts element identifiers and bounding boxes (Yarmohammadi & Castro-Lacouture, 2018), IFC loggers which capture snapshots and identify the changes made between different versions of BIM models (Kouhestani & Nik-Bakht, 2020; Pan & Zhang, 2021), and command-object graphs to notate the geometric modeling sequence (Gao et al., 2021) to improve the understanding on modeling patterns. However, these custom logs still grapple with reproducing the BIM authoring process due to missing information to represent the geometric shape and attributes of the building elements.

The BIM authoring process is often defined as a process in which 3D software is used to develop a BIM model based on criteria that are important to the translation of the building's design (Messner et al., 2019). Accordingly, this process includes the addition, deletion, and modification of the geometry of building elements and their associated properties (Kouhestani & Nik-Bakht, 2020; Lin & Zhou, 2020). Through BIM authoring, building elements are refined to meet the level of development (LOD)—the information necessary to depict the building elements—within the BIM model. However, the BIM model only reflects the end result of the comprehensive BIM authoring process. Concurrently, the design decisions made during this process can be a rich and invaluable reservoir of information, encapsulating real-time design decision-making. Documenting these design decisions can also aid in extracting the design knowledge of architects, especially when paired with recently emerging data-based analysis techniques (Jang et al., 2023). In this context, this study aims to develop a custom logger designed to capture essential information, enabling the reproduction of the BIM authoring process.

3. METHODOLOGY

This study developed a three-step methodology to enhance the reproducibility of BIM logs as depicted in Fig. 1. The methodology involved developing a customized BIM authoring logger, implementing a BIM authoring process reproducer, and evaluating the reproducibility of the enhanced BIM log through a case study.

Fig. 1: Research flowchart.

To capture sufficient information in the BIM log to reproduce the BIM authoring process, the authors analyzed the minimum inputs required to represent building elements in Revit. As building elements are represented using classes in an object-oriented programming model, the information required for each class corresponding to a specific category of elements was analyzed. The log captures the geometric shape and attribute values to represent the building elements in a comma-separated value (CSV) format. The reproduction algorithm developed in this study iterates through the events recorded in the BIM log, identifies the command type (i.e., "ADDED," "MODIFIED," or "DELETED"), and executes them with reference to the "Comments" property (i.e., copied "ElementID") of the building elements.

The evaluation phase of this study involved modeling Villa Savoye designed by Le Corbusier for the case study, during which the BIM authoring logger recorded the authoring process (Fig. 2). The events recorded in the enhanced BIM log were iterated using the BIM authoring process reproducer, and the reproducibility of the developed model was evaluated based on the volumetric center distances and volume differences between elements, as well as visual analysis of plans, elevations, sections, and 3D views.

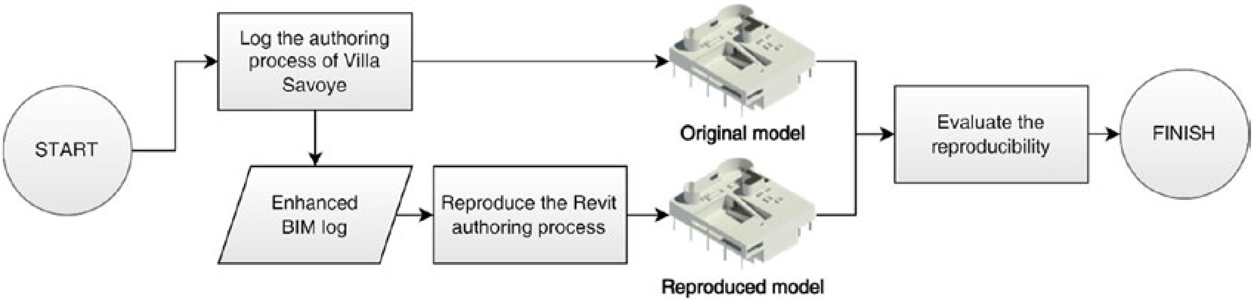

Fig. 2: Evaluation of BIM authoring logger and BIM authoring log reproducer.

4. ENHANCED BIM LOGS

This section provides a detailed overview of how building elements are defined in Revit and how the enhanced BIM log captures the necessary information to accurately represent the BIM authoring process. The study utilized Autodesk Revit 2023 and Revit C# API for the implementation of the enhanced BIM log. Building elements in Revit are represented using classes in an object-oriented programming model that has a hierarchical structure that reflects the physical structure of the building. Each class corresponds to a specific type of building element, such as walls, floors, roofs, doors, and windows. Fig. 3 illustrates the geometric shape and attribute values recorded for each building element category.

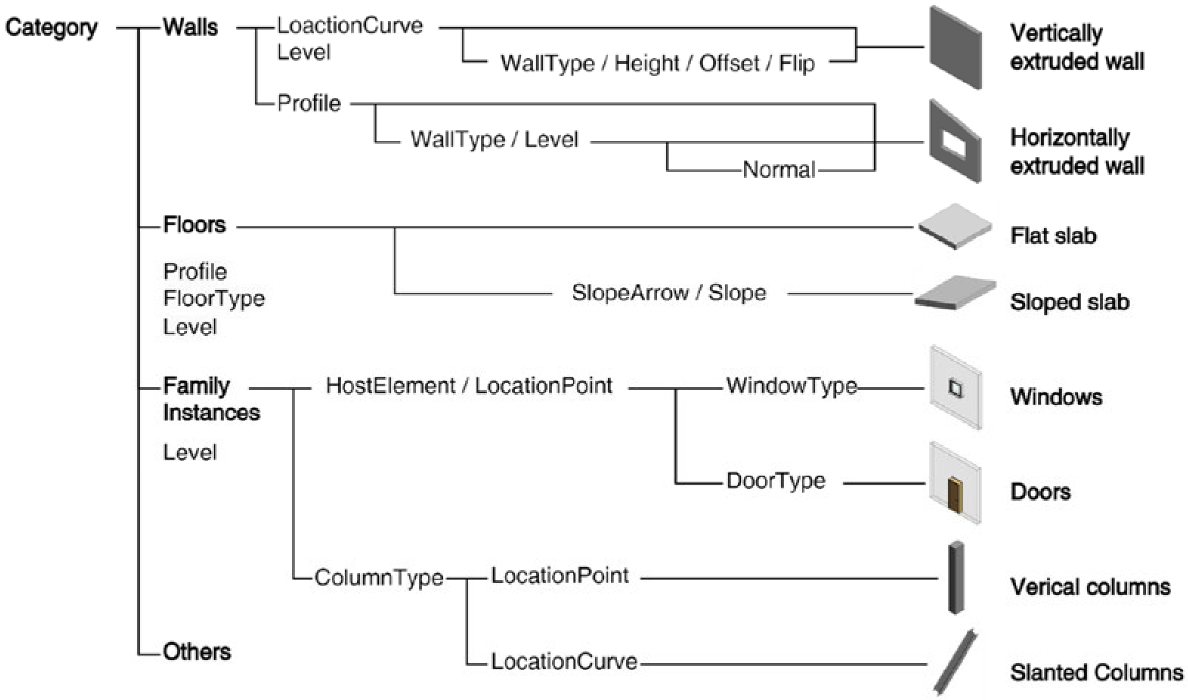

Fig. 3: Geometric shape and attribute values recorded within the enhanced BIM log.

Wall elements in Revit are classified into two categories—rectangular profile walls and nonrectangular profile walls—following the different creation methods for each type. Floor elements are classified into two types, flat floors, and sloped floors, and are created using different attributes depending on the type. Windows, doors, and columns are classified as "FamilyInstances," and their representation is based on the placement of predefined instances on the selected base geometry. "FamilyInstances" have different categories based on the "FamilySymbol" used, such as "WindowType," "DoorType," and "ColumnType." Windows and doors require a "LocationPoint" and "HostElement," while columns can be placed without a "HostElement," depending on whether the representation of the slope is required.

In addition to recording other required information items as string formats, the enhanced BIM log captures geometric bases, such as "LocationPoint," "LocationCurve," and "Profile," and their respective subclasses, such as "Line," "Arc," "CylindricalHelix," "Ellipse," "HermiteSpline," and "NurbsSpline." The information required for each geometric base and its string format representation is presented in Table 1. The enhanced BIM logger records the geometric bases of the building elements represented during the BIM authoring process in the described format.

Table 1: Definition of geometric classes.

Classes	Subclasses	Input Requirements	String Formats
Location Point	XYZ	(X coordinate, Y coordinate, Z coordinate)	(double, double, double)
Location Curve	Line	(endPoint1, endPoint2)	[Line, XYZ, XYZ]
	Arc	(plane, radius, startAngle, endAngle)	[Arc, XYZ, double, double, double]
	CylindricalHelix	(basePoint, radius, xVector, zVector, pitch, startAngle, endAngle)	[CylindricalHelix, XYZ, double, XYZ, XYZ, double, double, double]
	Ellipse	(center, xRadius, yRadius, xAxis, yAxis, startParameter, endParameter)	[Ellipse, XYZ, double, double, XYZ, XYZ, double, double]
	NurbsSpline	(degree, knots, controlPoints, weights)	[NurbsSpline, int, IList<double>, Ilist<XYZ>, Ilist<double>]
	HermiteSpline	(controlPoints,periodic,tangents)	[HermiteSpline, Ilist<XYZ>, bool, HermiteSplineTangents]
CurveLoop	CurveLoop	(LocationCurve_1, …, LocationCurve_n)	{CurveLoop, LocationCurve_1, …, LocationCurve_n}
Profile	Profile	(CurveLoop_1, … ,CurveLoop_n)	Profile, CurveLoop_1, … ,CurveLoop_n

Furthermore, multiple attribute values in Revit can be modified to better represent each building element. For instance, recording whether it was flipped was important in representing vertically extruded walls because the sequence of the wall layer can be positioned opposite. Meanwhile, a normal vector that the wall is facing is critical in the horizontally extruded walls. The initial values and modifications of the attributes are also recorded in the enhanced log, providing information on how the building elements were defined and developed during the BIM authoring process.

5. REPRODUCTION ALGORITHM

The authors implemented a reproduction algorithm to iterate through the events in the enhanced BIM log and repeat them, as illustrated in Fig. 4. The algorithm begins by identifying the command type of events. If the command type is "ADDED," the algorithm adds an element of the recorded category and applies the recorded attribute values, while adding the "ElementID" of the event to the "Comments" attribute of the newly created BIM element. If the command type is "MODIFIED," the algorithm queries the element with the "ElementID" recorded in the Comments value and applies the corresponding modification. If the command type is "DELETED," the algorithm queries the elements with the "ElementID" recorded in the "Comments" value and deletes the element.

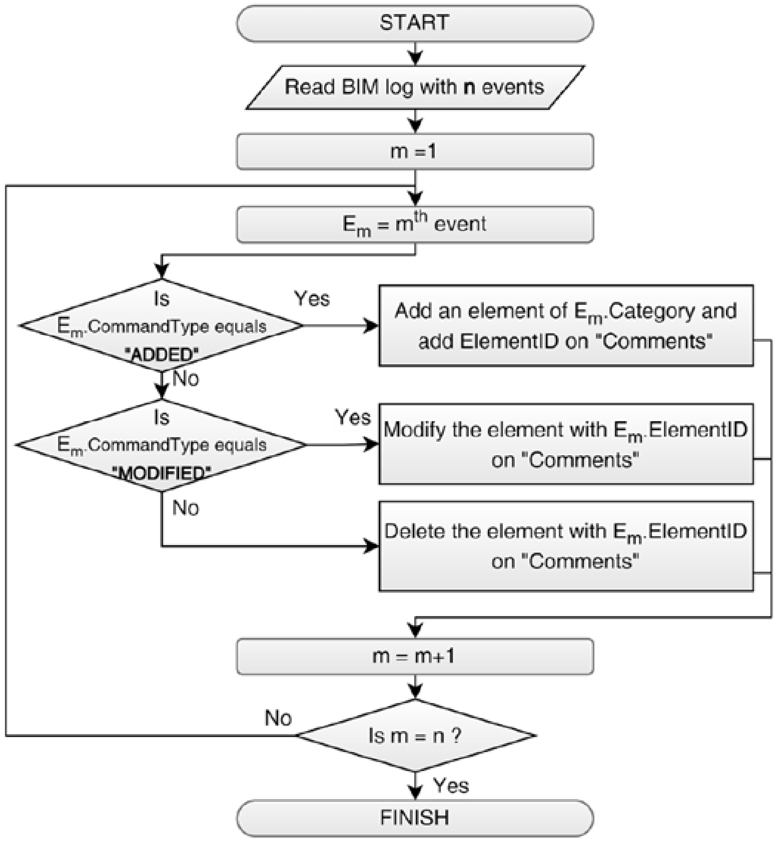

Fig. 4: Reproduction algorithm.

6. EVALUATION OF REPRODUCIBILITY

To assess the enhanced log and its ability to be reproduced, the authors of this study carried out a case study of Villa Savoye, designed by Le Corbusier. Using the BIM log from the authoring process, a reproduced BIM model was generated using the reproduction algorithm, as depicted in part (a) of Fig. 5.

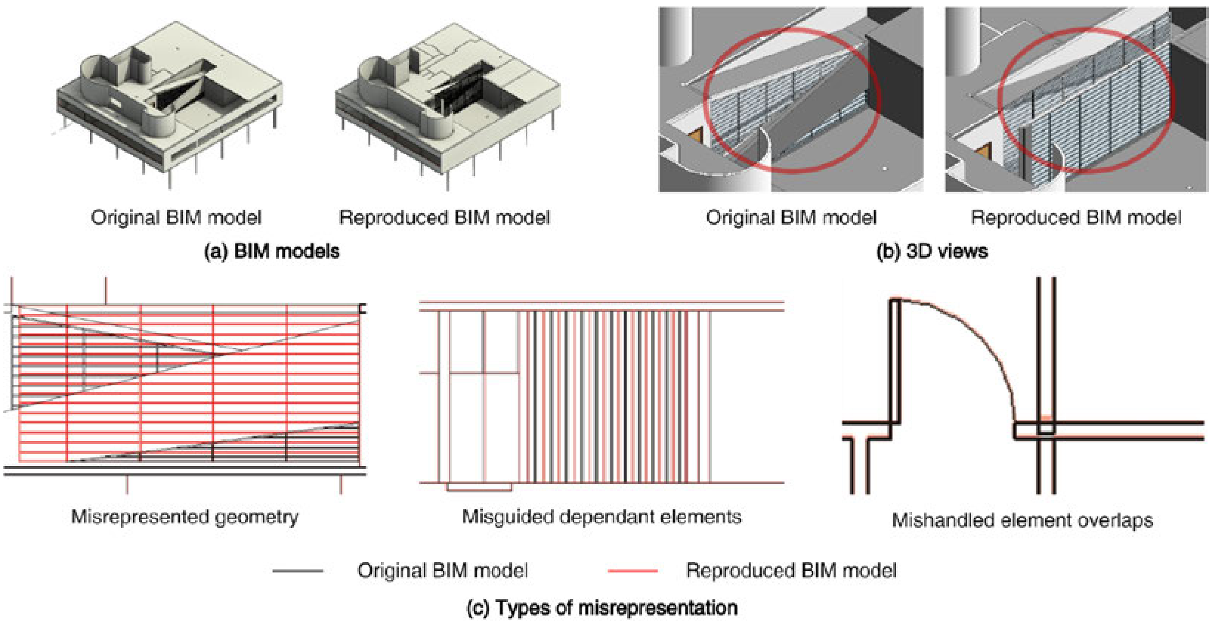

Fig. 5: Comparison between the original BIM model and reproduced BIM model.

The BIM model comprised 158 elements, which included 97 walls, 8 slabs, 8 windows, 19 doors, and 27 columns, with 2,836 events logged during the process. The reproduced model captured every element present in the original. A comparison revealed minimal average distances between the volumetric centers of the elements: 3.6440E-07 for walls, 2.1470E-07 for floors, 1.4760E-07 for windows, 1.6139E-07 for doors, and 1.4380E-07 for columns. Volume differences were also analyzed, with disparities noted as 0.1876% for walls, 0.0198% for floors, and 0.0433% for columns, with no discrepancies for windows and doors. The variations in distance and volume displayed a near-perfect reproduction. It is postulated that such differences may arise from metric and imperial unit conversions.

The models were contrasted visually in 3D, along with elevation, section, and plan views. The manual analysis allowed the authors to pinpoint inaccuracies in the reproduced model. As highlighted by the red ellipses in part (b) of Fig. 5, the curtain wall profiles were inaccurately depicted. Part (c) of Fig. 5 overlays drawings from the original and reproduced BIM models, delineated by black and red lines respectively. The comparison revealed three main types of inaccuracies:

Custom attributes: In this version of the implementation, custom attributes, such as distances between vertical mullions, were not supported. This omission led to mullions in the reproduced model being placed with default values. The issue was observed in four curtain wall elements.

Automatically connected elements: In instances where building elements overlapped, their placements varied occasionally. The function in Revit that automatically joins closely placed elements generates minor discrepancies in the lengths of the automatically joined elements, depending on how far apart the joined elements were initially. The issue was observed in two interior wall elements.

Unknown reasons: There were instances where the wall elements with specific profiles did not align precisely with the original design. These discrepancies may be attributed to limitations within the logging and reproduction algorithm. This issue was observed in six profile wall elements.

In summary, 12 of the 159 elements (or 92.45%) in the reproduced BIM models were inaccurately represented–all being wall elements. Despite these discrepancies, the enhanced BIM logger effectively logged most of the necessary information to recreate the BIM authoring process.

7. CONCLUSION

This study developed an enhanced BIM logger that captures the necessary information to reproduce the BIM authoring process. By analyzing the information requirements of five representative building elements in Revit, the authors developed a custom logger that records geometric shapes and attribute values. The study also developed a reproduction algorithm to repeat the BIM authoring process. The effectiveness of the enhanced log was evaluated in a case study of Villa Savoye designed by Le Corbusier, which showed that the enhanced BIM logger provides a valuable tool for capturing and reproducing 92.45% of the building elements generated and modified within the BIM authoring process. While minor discrepancies and misrepresentations were observed, the results of the case study demonstrated the potential of the enhanced BIM logger.

Looking ahead, avenues for improvement lie in broadening the spectrum of building element categories or attribute values to augment reproducibility. Additionally, the applications of enhanced BIM logs beckon exploration, as does the prospect of analyzing the as-happened BIM authoring process (Shin et al., 2022; Yarmohammadi & Castro-Lacouture, 2018) and automating the BIM authoring process using such logs (Pan & Zhang, 2020). Overall, the enhanced BIM logger presented in this study can contribute to elevating the transparency and efficiency of the BIM authoring process, serving as an invaluable data source for its enhancement.

8. ACKNOWLEDGMENTS

This work was supported in 2023 by a Korea Agency for Infrastructure Technology Advancement (KAIA) grant funded by the Ministry of Land, Infrastructure, and Transport (Grant RS-2021-KA163269).

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TOWARDS CONSTRUCTION SAFETY MANAGEMENT MATURITY MODEL IN THE INDUSTRY 4.0 ERA: A STATE-OF-THE-ART REVIEW

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ABSTRACT: *While the advantages of leveraging advanced technologies and Industry 4.0 for effective safety management have been extensively recognized, the journey towards a more mature integration of Industry 4.0 technologies into safety management practices often lacks a well-defined and systematic guidance map. This research is a step towards providing organizations with a structured approach to navigate and achieve successful safety management transformation, enabling them to fully harness the potential of industry 4.0 technologies in the workplace. Two rounds of systematic literature reviews (SLRs) are conducted to narrow down the number of articles based on the PRISMA method, which are then subjected to further content analysis. The study highlights the integration of Industry 4.0 technologies within the domains of People, Process, and Policy and their significance in advancing safety maturity. This research uncovered key themes, providing valuable insights that will shape the conceptual maturity model structure of safety management based on the innovative nature of Industry 4.0 to enhance their safety culture to align with. The results provide a fertile ground for a Smart Safety Maturity Model, to integrate technologies to elevate safety drivers in construction safety management.*

KEYWORDS: *Industry 4.0, Maturity model, safety management, construction industry*

1. INTRODUCTION

The fourth industrial revolution, also known as Industry 4.0, in the construction industry, has been conceptualized as the application of innovative technologies and processes to improve the deliverance of tangible and intangible services within construction companies (Kumar et al., 2019). Construction contractors are adopting various technologies including robotics, advanced data analysis, immersive technologies, additive manufacturing, autonomous systems, cloud computing, cybersecurity, and the Internet of Things (Nnaji et al., 2019; Rüßmann et al., 2015; Smallwood & Allen, 2023). Although the construction sector increasingly adopts innovative technologies that go beyond conventional practices to address occupational Safety and health (OSH) constraints, there is no paved avenue for measuring their progress, benchmarking against standards and regulations, and pinpointing areas where efforts should be focused to achieve effective outcomes.

Maturity models (MMs) offer a structured transformational roadmap for organizations adopting new strategies like Industry 4.0 technologies for safety objectives and evaluate the current maturity level and plan for improved future performance (Alankarage et al., 2022; Paulk, 1995; Wendler, 2012). The structure of MMs is commonly organized into five stages or levels: initial, repeatable, defined, managed, and optimizing (Das et al., 2023; Rashidian, Drogemuller, Omrani, et al., 2023). The MMs also have a series of attributes and sub-attributes, mainly covering hard (technology-related aspects) and soft (human-related aspects) attributes (Rashidian, Drogemuller, & Omrani, 2023). However, their application has since expanded to various disciplines, including the construction industry (Rashidian et al., 2022). The current study heavily relies on using established Safety MMs available in the literature to understand the digital readiness in the existing safety MMs. The review of the MMs in the construction field by Rashidian et al. (2022) revealed that safety maturity is one of the key focus areas, covering two major themes safety culture and safety climate (Wilson & Koehn, 2000). Safety culture refers to the underlying beliefs and values that influence organizational behavior, while safety climate pertains to the attitudes and views of the workforce at a particular moment Griffin and Curcuruto (2016). While safety maturity models offer a structured approach for evaluating organizational safety progression, there exists a gap in understanding how the integration of technologies can effectively elevate safety maturity within construction processes. This gap raises the question of how technology can be strategically employed to benchmark and enhance safety practices. By addressing this research problem, organizations can better understand the synergistic relationship between technology adoption and safety progression, leading to optimized safety practices, improved risk mitigation, and ultimately safer working environments. The overarching aim of this study is to comprehensively analyze the correlation between Industry 4.0 technologies and the attributes of a construction safety maturity model. This involves a dual focus: firstly, to pinpoint the precise Industry 4.0 technologies that play a role in enhancing construction safety; and secondly, to conduct an exhaustive investigation into how these technologies are integrated within the existing Safety Maturity Models (MMs). By delving into the intricate relationship between Industry 4.0 technologies and construction safety maturity attributes, this study enhances the knowledge base surrounding the potential benefits and challenges of adopting Industry 4.0 technologies. It provides organizations with valuable insights into the

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FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Nazi Soltanmohammadlou, Sara Rashidian, Carol K. H Hon, Robin Drogemuller, Sara Omrani, *Towards Construction Safety Management Maturity Model in the Industry 4.0 Era: A State-of-the-Art Review,* pp. 515-525, DOI 10.36253/979-12-215-0289-3.50

ways in which technology can be harnessed to benchmark and enhance safety practices, ultimately leading to more effective risk mitigation strategies.

2. RESEARCH METHODOLOGY

A systematic literature search was conducted. Title, abstract, and keywords of peer-reviewed articles published from 2013 onwards. Our search was conducted exclusively within the cross-disciplinary database Scopus, which is recognized as the largest archive of peer-reviewed publications, including scientific reviews, collections of academic works, and conference proceedings (Hijazi et al., 2021). The identification phase of the PRISMA model was used as a framework for extracting relevant publications (Moher et al., 2009). The primary criteria for the initial filtering stage were defined, encompassing factors such as English language, academic relevance, and full-text accessibility. Subsequently, a preliminary assessment of content was carried out to ensure the presence of the required keywords within the titles and abstracts of the publications. Additionally, a reverse search approach was employed during this phase of searching and screening. Baker et al. (2023) mention to the approach as the "snowballing" technique which allows the acquisition of papers utilizing cross-references from the selected publications to minimize the impact of missing relevant resources. The systematic literature reviews (SLRs) were conducted through a two-phase approach, which is detailed in the subsequent subsections.

2.1 phase 1

We aimed to identify the utilization of maturity models in the realm of construction safety management. Following the removal of irrelevant articles, the total count of articles has been reduced to 11. Table 1 demonstrates how the connection between Boolean operators and the result of the search is represented in order to locate pertinent scientific articles.

Table 1*:* The PRISMA Identification stage results from searching the database (SCOPUS)

Search 1 Boolean operators (Searches done in July 2023)	Search Results Scopus
((“maturity model" OR "maturity framework") AND ("safety" OR "safety management" OR "risk" OR "risk management" OR "hazard" OR "accident" OR "accident prediction" OR "accident prevention") AND ("Construction site" OR "construction jobsite" OR "construction work zone" OR "construction industry" OR "construction workplace" OR "construction work*" OR "construction professional*" OR "construction labo*" OR "construction workforce*" OR "construction staff" OR "construction personnel*" OR "construction activit*"))	29

2.2 phase 2

Phase 2 is dedicated to retrieving papers associated with Industry 4.0 and safety management. The Scopus database yielded a total of 48 papers as shown in Table 2. Following a thorough evaluation of extracted papers, 26 papers were excluded based on the content of abstracts, as they were identified as irrelevant to the scope of the research. Then, a content analysis approach was employed to categorize highly interconnected terms, relying on researchers' semantic comprehension, to identify the various dimensions associated with them (Das et al., 2022). Due to the absence of a universally accepted definition of Industry 4.0, there is often a reliance on related terms to describe this paradigm (Das et al., 2022). Incorporating the keywords associated with each Industry 4.0 technology in the search led to a significant increase in the number of articles retrieved. Furthermore, a considerable portion of the papers examined did not propose dimensions that could be compared to existing safety maturity models. To ensure important references were not missed, manual searches of the references in the included studies and review articles were performed in addition to the electronic searches. Ultimately, through the process of reference tracking, an additional seven review papers were identified which covered the different applications of technologies in construction safety management, resulting in a total of 29 articles included in the review.

Table 2: The PRISMA Identification stage results from searching the database (SCOPUS)

Search 2 Boolean operators (Searches done in July 2023)	Search Results
	Scopus
(("industry 4.0" OR "4ir" OR "fourth industrial revolution") AND ("safety" OR "safety management" OR "risk" OR "risk management" OR "hazard" OR "accident" OR "accident prediction" OR "accident prevention") AND ("Construction site" OR "construction jobsite" OR "construction work zone" OR "construction industry" OR "construction workplace" OR "construction work*" OR "construction professional*" OR "construction labo*" OR "construction workforce*" OR "construction staff" OR "construction personnel*" OR "construction activit*"))	48

As can be seen in Fig 1., by combining the findings from Search 1 and Search 2, the findings and discussion were conducted to encompass the specific requirements of construction safety management while also addressing the essential elements needed to effectively navigate the challenges and opportunities presented by Industry 4.0. A total of 11 maturity models and 29 papers were curated from the outcomes of Search 1 and Search 2, correspondingly. Subsequently, each phase was independently analyzed to identify shared elements between them and how Industry 4.0 technologies improve the maturity of construction safety.

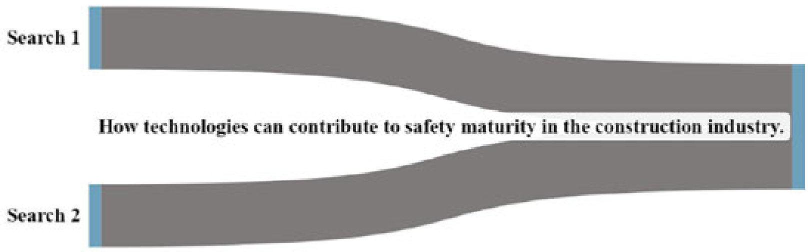
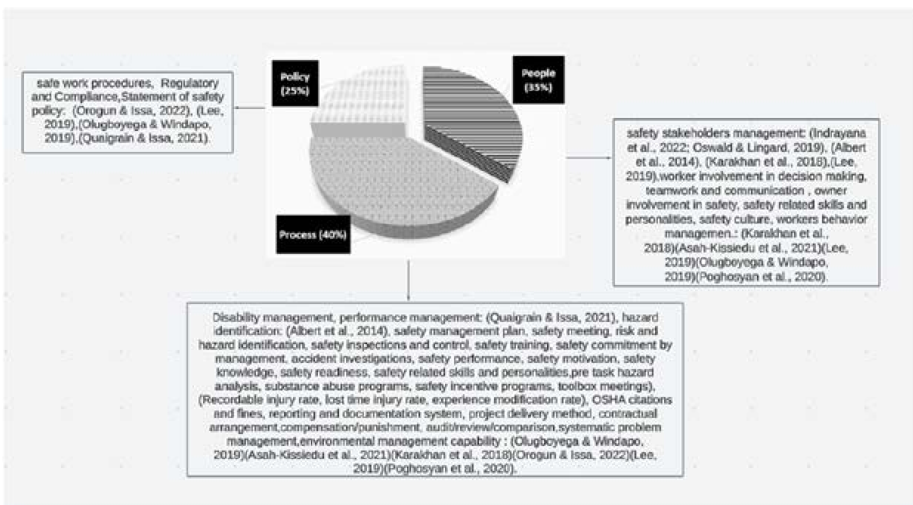


Fig 1. The goal of combining the findings from two-phase searches

3. CONTENT ANALYSIS

3.1 Publication distribution by safety maturity model attrinutes

Fig 2. has illustrated the distribution of publications based on their viewpoint on maturity models focusing on components. A total of 11 construction safety maturity models were extracted from phase one, each with distinct areas of emphasis classified under three main categories: people, process, and policy. The level of emphasis placed on regulation and standards maturity within models had the lowest hit when compared to other components. The apportionment of maturity models focus proximately reveals that the majority of maturity models' elements in the construction sector predominantly concentrate on managing various processes, while the second most prominent focus pertains to people as a foundational area in safety maturity models.



3.2 Publication distribution by industry 4.0 technologies application

The allocation of focus in Industry 4.0 technologies in Fig 3. which is extracted from phas two of search indicates that an equal proportion of attention, 39% each, is dedicated to both people and processes in the construction sector. These two areas are considered equally significant in the application of advanced technologies in construction safety management. The level of emphasis on improving regulation and standards through technologies was relatively limited comprising only 22% of the overall focus.

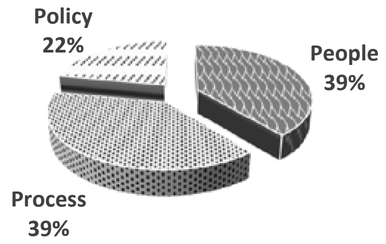


Fig 3. Publication distribution by industry 4.0 technologies applications

3.3 Publication distribution by industry 4.0 technologies type

Fig 4. in the literature encompasses a representation of the terminologies associated with various technologies. Among these, Artificial Intelligence (AI) and Industry 4.0 technologies have emerged as the most prominent and frequently referenced terms. The application of these technologies to aid safety challenges related to people, processes, and policy promote safety maturity in the construction process.

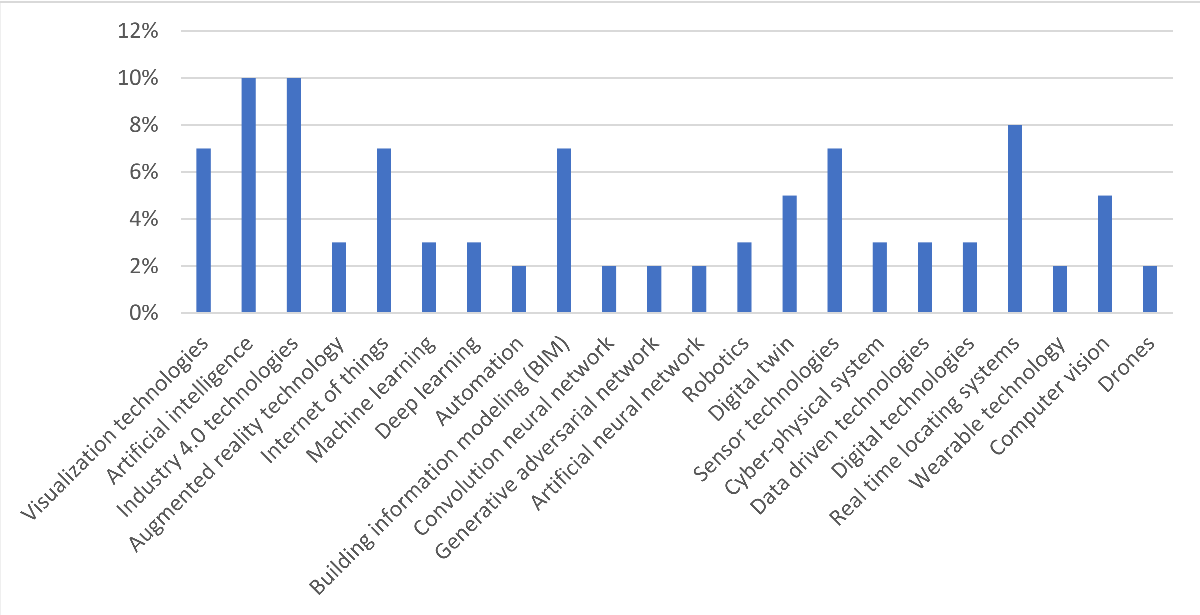


Fig 1. Publication distribution by industry 4.0 technologies type

3.4 Keywords co-occurrence in safety maturity models: insights from phase one search

A keyword network provides a visual representation and showcases the interconnectedness and intellectual organization of various research themes (Van Eck & Waltman, 2014). There are no universally defined guidelines for determining the frequency at which keywords should occur (Wuni et al., 2019). The frequency of the occurrence of the keywords as can be seen in Fig 5., among 28 keywords, the most important topics in the domain of construction safety maturity models extracted from phase one of search are related to cluster 1 labeled in red on the map had 8 members with keywords such as lagging indicators (e.g., job site safety audits, safety training, pre-task hazard analysis, and safety incentive program), leading indicators (e.g., recordable injury rate, lost time injury rate, and OSHA citations and fines), contractor selection, and decision making. Cluster 2 in the green region of the map had 7 items with keywords such as hazard awareness, hazard identification, safety accident, construction industry, occupation safety, safety management, labor, and personnel issues. Safety culture is the most important topic which has 18 links with other clusters.

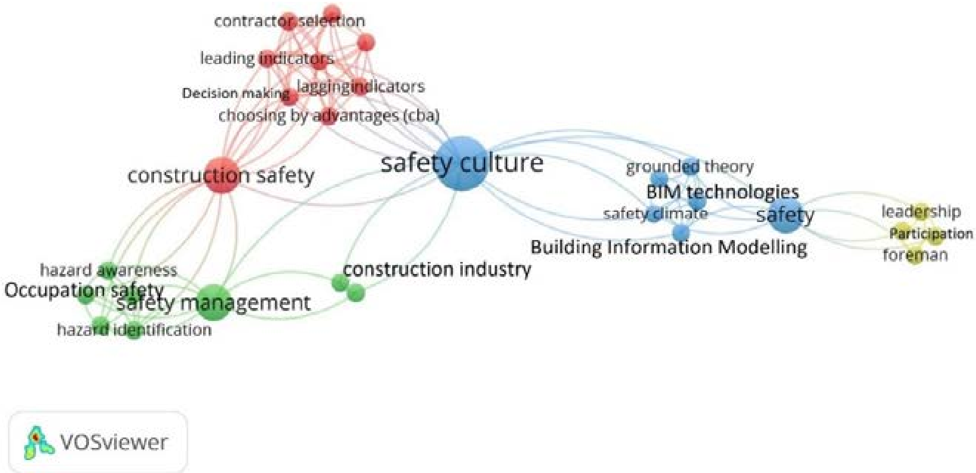


Fig 2. Co-occurrence of keywords of safety maturity models extracted from phase one of the search

3.5 Keywords co-occurrence in application of industry 4.0 technologies in construction safety: insights from phase two search

In Fig 6., the first cluster, indicated by the color red, represents the relevant technologies in the field of construction safety management such as artificial intelligence, automation, big data, digital twin, internet of things, machine learning, etc. The second cluster green shows links between Safety, technologies, and the construction industry, and cluster 3 dark blue shows keywords related to Industry 4.0 terms and their relationship to other clusters. The purple color cluster demonstrates how safety management has links with specific technologies such as sensor technologies, real-time locating systems, and visualization technologies. The last health and Safety, depicted in yellow, illustrates the opportunities and challenges arising from the adoption of technologies in the construction safety management domain after the fourth industrial revolution.

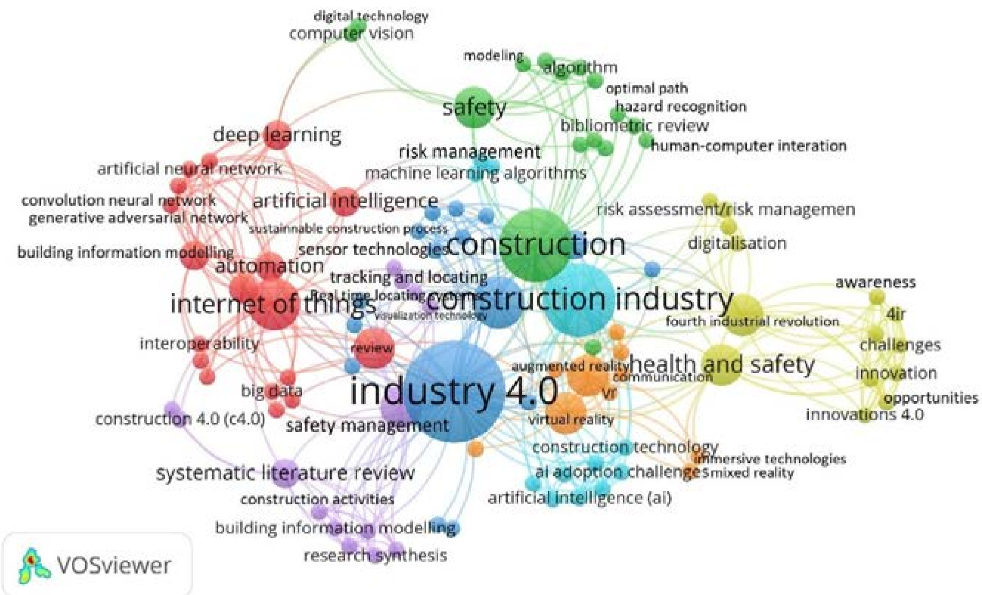


Fig 3. Co-occurrence of keywords of application of industry 4.0 technologies in construction safety extracted from phase two search

4. DISCUSSION

The thematic analysis of the drivers in the studied MMs revealed three major themes: Process, People, and Policy. This categorization aligns with other related literature, although slight variations exist. For instance, Succar (2010) utilized a BIM MM model and classified the drivers into three primary themes: People, Processes, and Technologies. Another context, as presented by Orogun and Issa (2022), involved categorizing the drivers in the health and safety assessment tool for Sustainable building projects, with the major themes being Building, Process and People. These findings emphasised the recurring significance of the Process and People themes in driving success in various domains while also highlighting the role of other drivers, such as technology or Buildings, in certain contexts.

4.1 Identification of safety drivers of maturity models in construction safety management

A body of literature focused on maturity models for Occupational Health and Safety (OHS) within the construction sector emphasizes the critical significance of leadership, commitment, engagement, effective communication, competence, and well-defined procedures as crucial elements in attaining maturity in this domain (Musonda et al., 2021). Assessing the maturity of Occupational Health and Safety (OHS) in construction projects also relies on the indispensable use of information and technology resources, along with facilitated collaboration made possible by technology (Poghosyan et al., 2020). Safety maturity also serves as a basis for evaluating safety performance (Karakhan et al., 2018; Oswald & Lingard, 2019) as well as disability management (Quaigrain & Issa, 2021). Construction frontline leaders play a crucial intermediaries role in transmitting messages between top-level management and workers, as well as bridging the gap between office-based and site-based people (Oswald & Lingard, 2019). safety leadership is a key factor in assessing causative incident factors and without supporting of leaders, workers are unable to effectively advocate for and implement safety behaviors (Indrayana et al., 2022). To establish a framework for evaluation and improving such practices, Oswald and Lingard (2019) developed a three-stage maturity model for revealing the relationships between foremen and subcontractor supervisors, the leadership styles of foremen and supervisors, the relationship between foremen and workers, the interaction between subcontractor supervisors, effective workgroup communication, and the relationship between frontline leaders and H&S advisors. Karakhan et al. (2018) also suggested a decision-making framework to assess the safety maturity of construction contractors which has seven main factors including safety leading and lagging indicators, Safety and supervisory personnel, system maturity and resiliency, preconstruction services, technology and innovation, and safety culture. Albert et al. (2014) suggested a maturity model for hazard recognition of workers to assist unanticipated hazardous conditions. A comprehensive framework in the work of Asah-Kissiedu et al. (2021) shed light on the various aspects of Safety, health, and environmental (SHE) management in construction operations. Table 3 illustrates the coverage of construction safety maturity research, showcasing components from different stages of construction safety management.

Table 3. Safety Drivers of maturity models in construction safety management

Reference	Maturity model	Safety drivers	Evaluation scope	Evaluation style
(Indrayana et al., 2022; Oswald & Lingard, 2019)	Frontline H&S leadership maturity model	People	Organization	Self-assessment
(Quaigrain & Issa, 2021)	Disability management Performance management	Process, Policy	Organization	Self-assessment
(Albert et al., 2014)	Construction Hazard Recognition and Communication with Energy-Based Cognitive Mnemonics and Safety Meeting Maturity Model	Process, People	Construction crew	Self-assessment
(Asah-Kissiedu et al., 2021)	Safety, health, and environmental management capability maturity mode (iSHEM-CMM)	Process, People	Organization	Self-assessment
(Olugboyega & Windapo, 2019)	Building information modeling—enabled construction safety culture and maturity model: A grounded theory approach	Process, People, policy	Organization	Self-assessment

(Lee, 2019)	Safety culture maturity model	Process, People, policy	Construction Site	Self-assessment
(Poghosyan et al., 2020)	Design for occupational Safety and Health: A capability maturity model	Process, People, policy	Organization	Self-assessment
(Orogun & Issa, 2022)	Evaluation of the health and Safety of sustainable building projects	Process, policy	Project	Self-assessment
(Karakhan et al., 2018)	Safety maturity model of contractors	Process, People	Organization	Self-assessment

4.2 Application of industry 4.0 technologies in construction safety management

Numerous investigations have explored the application of technologies in the domain of construction safety management (Asadzadeh et al., 2020; Babalola et al., 2023; Fargnoli & Lombardi, 2020; Sadeghi et al., 2021; Soltanmohammadlou et al., 2019). These investigations delve into various facets of the safety management process such as visualizing construction activities and hazards, data gathering, integrating health and Safety into construction activities, monitoring noncompliance, determining accident costs, linking requirements to construction activities, integrating health and Safety into the construction process, connecting information to construction activities, mitigating worker hazards, assessing health and safety costs, and monitoring health and Safety in construction processes and activities (Smallwood & Allen, 2023). According to Khodabakhshian et al. (2023), the correlation of big data, digital technologies, and artificial intelligence paves the road for covering various aspects of construction safety management. Based on extracted data in the content analysis section, there are three key focal areas of studies about the application of Industry 4.0 technologies in construction safety management.

4.3 Industry 4.0 technological solutions for process-related safety challenges

The integration of various technologies has forged paths toward embracing the safety challenges in the construction process (Statsenko, Samaraweera, Bakhshi, & Chileshe, 2022). The prevailing technology-driven solutions encompass a range of methods, including automating safety planning (such as job hazard analysis, safe work method statements, plan and design review, and organisational safety performance) through visualization technologies. Sensor-based location technologies play a significant role, as does on-site safety management (including optimizing safety processes, proactively preventing accidents, and enhancing the repository of safety knowledge), achieved, for example, through the integration of Big Data with Building Information modeling (BIM) or semantic web technology. Additionally, safety training, safety outcomes assessment, safety monitoring, safety program costs, and real-time hazard identification are facilitated through the utilization of technologies such as real-time location tracking, augmented reality (AR), and virtual reality (VR)(Pedro, Pham-Hang, Nguyen, & Pham, 2022)(Akanmu et al., 2021; Asadzadeh et al., 2020; Babalola et al., 2023; Fargnoli & Lombardi, 2020; Franco et al., 2022; Guo et al., 2017; Li et al., 2018; Malomane et al., 2022; Oke & Arowoiya, 2022; Perrier et al., 2020; Regona et al., 2022; Smallwood & Allen, 2023; Soltanmohammadlou et al., 2019; Statsenko et al., 2022; Wen & Gheisari, 2020).

4.4 Industry 4.0 technological solutions for people-related safety challenges

Industry 4.0 technologies find application in various domains of safety maturity elements, aiding in multiple areas. These include recognizing unsafe behavior, detecting worker hazardous motions, monitoring physiological indicators, capturing worker responses, facilitating communication-based safety, assessing worker capabilities, providing operator aids, enhancing the safety management system of main contractors, qualifying manufacturers, supervising main contractor site activities, nurturing workers' safety values, fostering safety culture, evaluating safety climate, and managing worker job stress. These domains benefit from the integration of Industry 4.0 technologies, including real-time locating systems, visualization technology, Internet of Things (IoT), wearable technology, and etc. (Awolusi et al., 2018; Fang et al., 2020; Franco et al., 2022; Guo et al., 2017; Malomane et al., 2022; Panteli et al., 2020; Sadeghi et al., 2021; Soltanmohammadlou et al., 2019; Statsenko et al., 2022).

4.5 Industry 4.0 technological solutions for policy-related safety challenges

Health and safety noncompliance, safety standards requirements, adherence to site safety rules, evaluation of equipment operators' compliance, and compliance with safety regulations form key areas of Industry 4.0 integration. This integration is facilitated through diverse technologies like digital twins, 4D models, real-time locating systems, Internet of Things (IoT) and etc within the framework of safety policies (Fargnoli & Lombardi, 2020; Franco et al., 2022; Malomane et al., 2022; Oke & Arowoiya, 2022; Panteli et al., 2020; Patrucco et al., 2020; Sadeghi et al., 2021).

4.6 Conclusion and future work

This research aims to determine how the identified Industry 4.0 technologies currently contribute to safety maturity models in the construction industry. The key findings of this research reveal a structured approach to advancing safety maturity within the construction industry in the context of Industry 4.0. Our findings highlight the paramount importance of integrating Industry 4.0 technologies within the realms of Process,People, and Policy to advance safety maturity. Additionally, it is essential to explore how these technologies offer solutions for challenges associated with processes, people, and policies in safety management.This categorization is mirrored in the classification of Industry 4.0 technology implementation, illustrating a direct alignment between safety progression and the adoption of Industry 4.0 technologies. The aim is to systematically organize the transformation of construction safety maturity models within the context of Industry 4.0 by identifying critical aspects of the contribution of technologies. Furthermore, the research underlines the pivotal role of technology, emphasizing its multifaceted contribution to enhancing safety practices and overall maturity within the construction sector.
In the existence of construction safety maturity model, there is no structured way to measure the contribution of technologies to attributes of safety maturity. The utilization of technology in contributing to the maturity level of safety in the construction process can also indirectly provide advantages to policymakers and government bodies to present the state of safety management in the construction industry in their region and establish specific goals and regulations accordingly. However, most Industry 4.0 technologies in the domain of construction safety management are immature and have not yet been comprehensively developed. This study paved the way for developing a Smart Safety Maturity Model which integrates technologies for improving safety in the construction process.

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INTEGRATED GEOBIM REQUIREMENTS DEFINITION FOR DIGITAL BUILDING PERMIT

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ABSTRACT: *The development of methods for building permit issuing supported by digital tools could improve the current mostly manual procedures for processing regulatory information and related compliance processes. Several studies are currently addressing the challenge of building permit digitalisation, mostly considering building information models as the source data for automating the regulations checks. However, many of the main checks, that usually represent the major bottlenecks of the compliance checking process, need a joint representation of the new proposed construction and its context, which could be effectively represented in a (3D) geographical information system. This study aims at supporting the automation of building permitting by addressing the rule interpretation as an input to model preparation and code checking. In particular, the regulations interpretation in this case is functional to the definition of data requirements and checking rules referring to a joint GIS and BIM (GeoBIM) framework. The approach is developed and tested in the case of an Italian municipality of 45.000 inhabitants. This paper describes the interpretation of distance-related regulations by adopting a semantic mark-up and sentence-centric approach. The resulting level of information need has been represented in conceptual models (object, attributes, relationships) as an essential input to city and building model preparation. While the case study is specific in location and regulations, the type of issues encountered are a generally applicable example for the building permit use case. Future works will extend the methodology to additional three European municipalities between 45.000 and 1.000.000 inhabitants, in three European countries, to address the need for a flexible and scalable approach.*

KEYWORDS: *Digital building permit; Rule interpretation; GeoBIM; Information requirements; Building-urban interaction.*

1. INTRODUCTION

A building permit is an authorisation required to start the construction phase of a building and it is granted by public authorities after verifying that the design proposal complies with construction regulations at building and urban levels (Noardo, *et al.* 2022). Building permit checks are traditionally a time-consuming and manual procedure for municipalities and the process is recognised as poorly effective due to multiple factors including, but not limited to, the technical knowledge of public officers in the assessment and the high demand for building permits to be inspected, troubled by the lack of adequate personnel (Fauth & Soibelman, 2022). Also, procedures for the issuance of the permit tend to be complex because of having to adapt to frequent legislative updates (Malsane, *et al.* 2015).

The development and connection of methods for building permit issuing supported by digital tools could improve the current as-is manual procedures for processing regulatory information and related compliance processes. With the increased adoption of Building Information Models (BIM) in building design processes, several municipalities are investing in automating these checks both by using BIM methods and tools, but also by increasingly integrating them with the geographic datasets at their disposal (Hobeika, *et al.* 2022). Research in the adoption of BIM to design verification for regulatory compliance is not recent - think of the discussion on BIM-based rule checking proposed by Eastman, *et al.* (2009). However, until a few years ago, research works were mainly focused on analysing building data, including their conversion in building-related neutral data schema as Industry Foundation Classes (IFC), rather than integrating BIM and Geographic Information System (GIS) (i.e., GeoBIM) (Hobeika, *et al.* 2022).

It is clear how important checks for the issuing of building permits require constant interaction between data on

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Silvia Mastrolembo Ventura, Sara Comai, Francesca Noardo, Kavita Raj, Angelo L.C. Ciribini, *Integrated GeBIM Requirements Definition for Digital Building Permit,* pp. 526-537, DOI 10.36253/979-12-215-0289-3.51

the building for which permission to proceed with the construction phase is sought – to be retrieved in the building information model - and information about the urban context in which it is located – to be retrieved in geo-data sets or 3D city models. This means that without adopting a GeoBIM approach some checks would require users to manually add information that should be instead automatically extracted from geo-data sets. For example, many urban parameters depend on urban zones, a new building must comply with minimum distance criteria from existing ones, interaction with existing public or private facilities must be considered, as well as public transport, parking standards and so on (Hobeika, *et al.* 2022). For this reason, according to recent studies on digital building permit (DBP), the automation of the checking of those kinds of regulations can only be effective if both geo-data and building data are considered. At present, the adoption of a GeoBIM approach represents a significant challenge of the DBP use case (Arroyo Ohori, *et al.* 2018). Recent literature, especially from 2016 (Noardo, *et al.* 2022), investigate the management of geo-data by available standards (e.g., CityGML) (Guler & Yomralioglu, 2021) and GeoBIM interoperability (e.g., conversion of 3D city models to BIM) (Nebras, *et al.* 2020) as essential steps for allowing designers to consider geoinformation as a suitable reference (Noardo, *et al.* 2022).

This paper focuses on rule interpretation, the process of conversion of the natural language of city and building regulations into computable parameters and constraints. Within the broader research framework, the methodology adopted for the interpretation of *distance-related* regulatory requirements and their formalisation is described in Section 2. Distance-related checks are one of the examples of regulatory checks that need the adoption of an integrated GeoBIM approach to be automated. Results from the interpretation of regulatory requirements from a specific case study are described in Section 3, including the formalisation of the relevant level of information need as a preliminary input to city and building model preparation and code checking (Section 4). Finally, limitations of the study, which is currently ongoing, are discussed along with future contributions (Section 5).

2. RESEARCH FRAMEWORK AND METHODOLOGY

The research considers the digitisation of the building permit use case for an Italian municipality of 45.000 inhabitants (i.e., Municipality of Ascoli Piceno). It has been explored in close collaboration with the municipality, and it is based on the field experience of its own officers. First, the list of checks to be digitised for effectively supporting the building permit process has been defined. Then, regulations among the ones that were deemed likely to have the best advantage from GeoBIM have been considered as a priority by municipality officers. They include: maximum buildable urban volume, buildability index, covered area, coverage ratio, maximum building height, building protrusions on public streets and squares, parcel's fence height, distance from other buildings (i.e., building-building distance), distance from the parcel boundaries (i.e., building-parcel boundaries distance), building-road distance, parking standards (dimensions/area and n. of parking spaces).

In this paper the results regarding *distance-related* regulations are described. Those regulations were selected, in consultation with municipality experts, because these were judged to be among the most important ones to be implemented. Distance-related regulations have been classified as follows: building-building distance, building-parcel boundaries distance and building-building distance if a road is interposed. The specific text of the regulation has been analysed with the aim of translating it into a set of information requirements for the DBP use case and, on the other hand, into a machine-readable format. The former objective lies within the scope of this paper, while the development of a pseudocode, developed based on this initial discussion, will be a future work of this research which is still ongoing.

2.1 Rule interpretation

Rule interpretation represents the first step of the DBP workflow (Figure 1) but it is also one of the main challenges in such a use case. The relevant information in documents such as public laws, codes and regulative standards should be captured in a time and cost-effective way to be able to adopt rule checking effectively (Noardo, *et al.* 2022). However, the complexity of the natural language used for regulatory requirements and its interpretation into data sets for supporting the adoption of a digital approach represents an open issue for automating and digitising design compliance checking and, specifically, building permitting. Malsane, *et al.* (2015) describe how knowledge formalisation of building codes could provide "suitable, significant and required data for the development of the building regulation-specific object modelling". They claimed how the formalisation of building regulations should include the classification of regulation clauses into "those which are computer-interpretable (declarative) and those which are not (informative)". The former provides a direct meaning to be interpreted (e.g., simple geometrical rules which when applied to an element can return true or false), while the latter contain data only partially suitable for interpretation into computer rules that can be processed (e.g., information is not obvious as checkable, needs human interpretation to understand the exact content and meaning). Finally, a remaining category of clauses exist that can be considered as unsuitable for automated compliance checking.

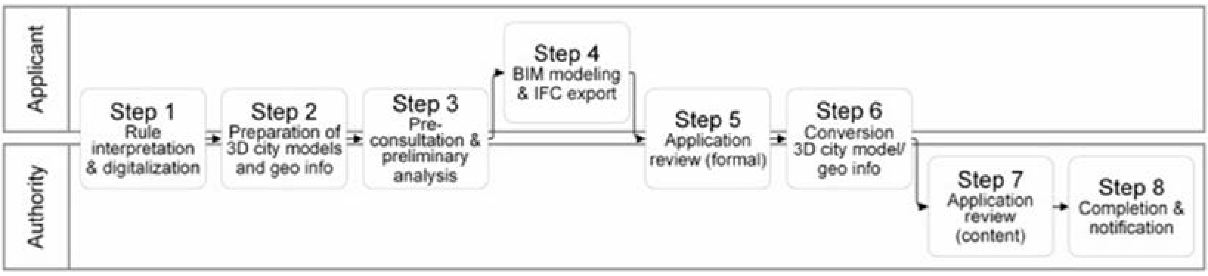


Fig. 1: Overview of considered DBP workflow steps assigned to involved parties (Noardo, *et al.* 2022)

Several rule interpretation processes are described in literature, both manual-based and automatically enabled, to create computable representations of normative data (Dimyadi, *et al.* 2017). Studies exist that propose methods to automatically interpret the natural language of regulations transforming them to code to check the proposed building design, as represented in building information models (e.g., Song, *et al.* 2018; Zhang & El-Gohary, 2017). However, challenges appear long before the conversion of this information from natural language to any formal language since even for human beings the interpretation of the text, tables and graphical contents of regulations can be open to different interpretations (Noardo, *et al.* 2020). According to Zhang, *et al.* (2023), the ambiguity of building requirements is one of the main issues since it could prevent their accurate interpretation and automated checking. They discussed how some ambiguous clauses in building requirements "reflect regulators' intention while others are unintentional, resulting from the use of language or tacit knowledge". Even if the rule interpretation process could rely on the programmer's interpretation and translation of the written rules into computer code (Eastman, *et al.* 2009), in most cases the logic of the human language statements is first formally interpreted and then translated. In fact, because of the complexity and subjectivity in nature of building regulations, as just mentioned, building regulation experts (e.g., municipality officers) need to be involved in their conversion to computer interpretable rules to ensure the correct interpretations (Malsane, *et al.* 2015).

In this study, a sentence-centric approach and a semantic mark-up procedure have been adopted for rule interpretation. Each regulatory article that municipality officers considered as significant for distance-related checks was interpreted (i.e., sentence-centric approach). To this end the *Requirement, Applicability, Selection, and Exception* (RASE) methodology has been adopted for deconstructing rule sentences and to extract semantics from building regulations for compliance checking (Hjelseth & Nisbet, 2011; Nisbet, *et al.* 2022). The content of regulatory requirements has been interpreted by dividing each sentence into these four basic components to support formalisation (i.e., semantic mark-up procedure). Such an approach to rule interpretation can be seen as a pre-processing step as in this case the result cannot be directly interpreted by the computer (Preidel & Borrmann, 2018).

Moreover, a relevant step to solve ambiguities has been performed by the organisation of a specific meeting with the involvement of municipality officers who usually check and then release or deny the building permits themselves. The details and meanings of the distance-related regulations were explained and agreed upon and specific questions were asked about ambiguous statements. Moreover, some more details arising during the following work towards implementation were asked later. That was the only way to have ambiguities about the regulation solved. This issue already showed how little the current state of regulations lends itself to automation (Noardo, *et al.* 2020).

After that, the regulation was formalised step by step. A table containing the metric phrases identified through the RASE labelling has been compiled and the following data set has been provided (Hjelseth & Nisbet, 2011; Tomczak, *et al.* 2022): the object to which the rule refers, the type of information to be verified (i.e., property), the data type (e.g., text, number, boolean) of the required properties, the comparison (e.g., ≤, ≥, contains), the value to be compared (i.e., target value), the unit of measurement that the value should have (i.e., for numerical values) and, if necessary, dependencies and application conditions. Plain text description could be added to support unambiguous definitions and information requirements could also demand a particular level of detailedness to support building and city model preparation, meaning what needs to be modelled and to what precision (i.e., geometrical data) (Tomczak, *et al.* 2022).

2.2 Information conceptual models

Based on the results from rule interpretation, information requirements have been identified and formalised in terms of information conceptual models (object, attributes, relationships) as an essential input to city and building model preparation (Zhang, *et al.* 2023). Both building and city models are sources of information involved in automated compliance audit processes if a GeoBIM approach is adopted. They respectively represent the building design to be audit - usually developed by the professional responsible for applying for a building permit on behalf of the applicant - and the urban context in which it is located. Another source in the automated compliance checking process is represented by normative clauses structured in machine-readable formats, which is not within the scope of this paper.

Conceptual models, in the practice of database design, are intended to formally represent the information to be stored in a database. The database design methodology defined by the ANSI/X3/SPARC standard defines four levels of data modelling: external model, representing a simple narration of requirements for information representation of the database; conceptual model, abstracting and formalising the information requirements in the external model into objects (i.e., entities or classes), the respective properties or characteristics (attributes) and reciprocal relationships; logical model, converting the conceptual model into rules more computing oriented; and finally the internal, or physical model, corresponding to the actual implementation format of the database (Laurini & Thompson, 1992).

In this study, the information about requirements was collected from the regulations, and the mark-up phase through the RASE methodology facilitating the formalisation of the regulatory contents was one intermediate step supporting the definition of data requirements as conceptual models, which were represented following the Unified Modelling Language (UML) (OMG, 2023). Objects and related attributes needed for distance-related checks in the DBP use case for the considered municipality have been identified. The representation includes data types and specifies if data are directly extractable from the model (e.g., the height of the object) or whether they need to be entered manually by the designer. For numerical value the type is specified (e.g., integer, real, float), while for textual data allowed classifications are specified from which data values can be chosen (e.g., the list of actual intended uses for the municipality's urban zone from which a designer has to choose before submitting its design to the building permit procedure. Depending on the type of intended use of the urban zone, in fact, some regulatory constraints will apply over others). The conceptual model representation also allows the type of relationship (aggregation relationship, composition relationship, etc.) to be specified.

Finally, the development of the conceptual models supports an easier comparison and harmonisation of the information requirements according to the same type of check (e.g., distance-related check) applied in different municipalities or according to different types of checks applied by the same municipality. This will facilitate the mapping to standards for representing BIM and GIS-related information consistently in future steps. To this end, as a preliminary step, for the objects in the conceptual model proposed in this paper it is specified whether they should belong to the BIM or GIS information representation.

3. RESULTS FROM THE INTERPRETATION OF REGULATORY REQUIREMENTS

The regulation considered here is the *Regolamento edilizio comunale (i.e., Building code) of the Municipality of Ascoli Piceno.* Municipality officers pointed out Article 61 of the text, reported here in paragraphs 2, 3, 4 and 6, as important for distance-related checks. The text translated into the English language is available in Table 1.

When considering this Article for formalisation, several examples of the complexity of the natural language of regulatory requirements emerges. For example, paragraph 2 refers to another regulatory text whose requirements, in relation to the one under analysis, are not made explicit. A reference to the "*urban planning instrument",* which could contain additional requirements, is also mentioned in the paragraph. The prescribed minimum distance between two buildings is implicit in the text – referring to the *"height of the tallest building"* - and refers to another regulatory aspect concerning the maximum building height, for the explication of which it is necessary to refer to further definitions or regulatory articles. The same happens for the distance of the building from the boundaries of the parcel in which it is located (i.e., "*the distance of a building from the parcel boundaries shall be equal to the half of the maximum permitted height"*). Paragraph 4 also refers to additional definitions, such as the one of the distances of a building from a road: what does the road should contain as an object in city or building information models?

It is therefore essential to interpret not only the regulatory requirements but also definitions contained in building regulations and other regulatory texts that are relevant to the inspection in question. In 2016, an agreement was reached between the Italian state, Regions and the National Association of Italian Municipalities to adopt the so-called Standardized Building Regulations to simplify and unify actions in building matters. To this end, a set of forty-two uniform building-urban definitions was also developed, which represents the common glossary valid throughout the country. However, the process of transposing the Standard Building Regulations and their homogeneous definitions is still in progress and it is currently not possible to proceed with an unambiguous interpretation of them that has generalised validity. In this case, the regulation considered here is the *Regolamento edilizio comunale of the Municipality of Ascoli Piceno – art. 13 (o, p, q).* The text of these definitions translated into the English language is contained in Table 2, which also contains the graphical interpretation of the definitions as proposed by the authors and validated by municipality officers. The definition of building height (art. 13, paragraph m and n) had to be considered as well and it is contained in Table 3.

Table 1: *Building code of the Municipality of Ascoli Piceno. Art. 61 (i.e., distance-related checks)*

Paragraph	Text of Normative Article
2	In (c) areas of expansion referred to in Article 2 of Ministerial Decree No 1444 of 2 April 1968, published in the Official Gazette of 16 April 1968, No 97 between windowed walls of facing buildings, a minimum distance is prescribed, equal to the height of the tallest building and no lower than 10 m; if the facing facades overlap for more than 12 meters, the rule applies also when only one of them has windows. In the same urban zones, the distance of a building from the parcel boundaries shall be equal to the half of the maximum permitted height and in any case not less than 5 m. Construction on parcel boundaries is allowed, where permitted by the urban planning instrument, by agreement between the neighboring owners
3	For all construction operations in other areas, the following minimum distances are prescribed: (building-building distance) (1) between windowed walls and walls of buildings in front of which at least one window: ml. 10; (building-parcel boundaries distance) (2) from the boundaries: ml.5 and unless otherwise prescribed by the general urban planning instrument.
4	Minimum distance between buildings with roads in-between, excluding cul-de-sac roads serving single buildings or settlements, must be equal to the road width plus: (1) 5.00 m per side, in case of streets width lower than 7.00 m, (2) 7.50 m per side, in case of streets width between 7.00 and 15.00 m, (3) 10.00 m per side, in case of streets width higher than 15.00 m
6	It will not be taken into account for the purposes of determining distances, overhang structures such as steps and open external stairs (maximum height 4), (1) gutter frames, open balconies and canopies, provided that the relative outline remains spaced from the boundaries at least by 1.50 m; (2) While account shall be taken of anybody closed in protrusion whatever is the adjective and at whatever height of the building it begins.

Several ambiguities and uncertainties also arise for human interpretation. Those were mainly solved with the help of municipality officers in a meeting organised on the 17th of May 2023. Later, further ambiguities have been solved thanks to the continuous collaboration with the municipality, which was critical for the success of this initial phase. For example, the *building-building distance* can be considered radially or perpendicularly to the new building. Through discussions with municipality officers, it was defined that the segment defining the distance is perpendicular to the line of the building (see Table 2, paragraph o). Considering the building-road distance check, doubts emerged in relation to the “road furniture areas”. Talking with the municipality officers it was possible to define the entity of “flowerbed” to which the normative text refers (see Table 2, paragraph q).

Results from rule interpretation have been formalised in a table containing the metric phrases identified through the RASE labelling as described in Section 2 (Figure 2). In Figure 2, the identified values for distances only apply to one urban zone, namely the c) areas of expansion. The first part of the article identifies the distance between two buildings with external windowed walls (art. 61(2) – case a), while in the second part, the overlap factor intervenes (x >12 m) (art. 61(2) – case b) and the distance is calculated between two walls of which at least one is windowed, so we have two cases, the existing building with a wall containing a window and the new building without windows or vice versa, the new building with a window and the existing building without (Figure 3).

Table 2: Distances-related definitions as defined in the *Building code of the Municipality of Ascoli Piceno, Art. 13*

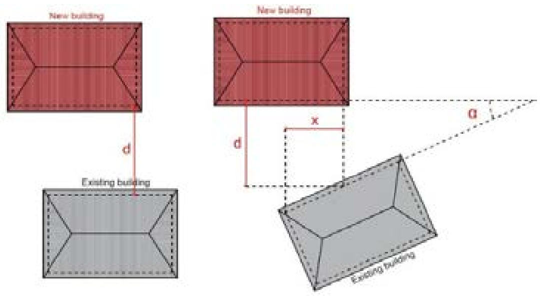
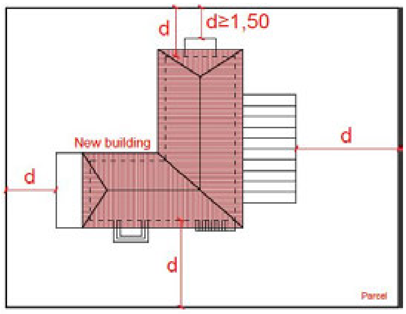
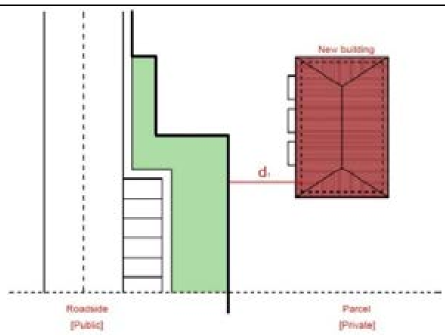
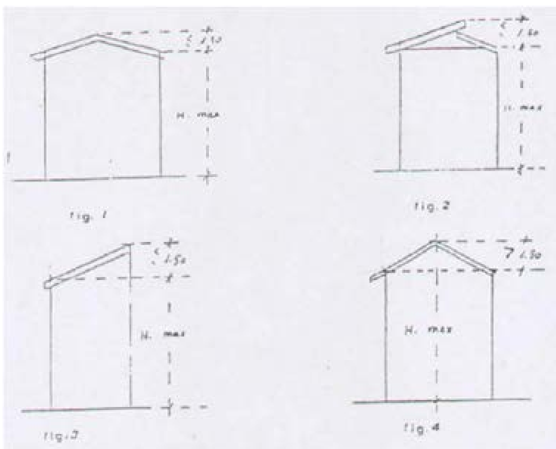
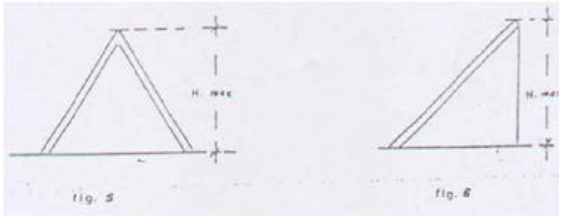
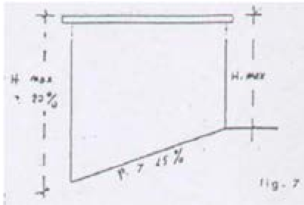
Regulatory requirement	Graphical interpretation
Paragraph o – Building-building distance. Is the distance (minimum) between the walls in front of the buildings, or buildings of the same, except for the walls on the interior spaces referred to in point (r) below, measured at the points of maximum protrusion. Two walls are considered to be facing when the angle formed by the extension of the same is less than 70 degrees sexagesimal and the overlap is greater than 1/4 of the minimum distance of the walls themselves. For graded buildings, the distance is measured at each setback.	
Paragraph p – Building-parcel boundaries distance. It is the distance between the vertical projection of the wall of the building and the boundary line, measured at the point of maximum protrusion. It is understood as a border beyond the separation line of the different existing properties or the line defining the different lots or compartments of the implementation plans, as well as the line of delimitation of public areas for services or equipment identified in urban planning instruments.	
Paragraph q - Building-building distance if a road is interposed. It is the distance between the vertical projection of the wall of the building and the edge of the road, including sidewalk and public parking and road furniture areas.	

Table 3: Building-height definitions as defined in the *Building code of the Municipality of Ascoli Piceno, Art. 13*

Regulatory requirement	Graphical interpretation
Paragraph m - Front height (H) - This is the height of any part of the elevation into which the building can be broken down, measured from the ground line to the roof line, taking into account the setback bodies if not included. The ground line is defined by the intersection of the wall of the elevation with the street level or the plane of the pavement or the plane of the ground at final settlement. The roof line is defined, in the case of a flat roof, by the intersection of the elevation wall with the plane corresponding to the extrados of the roof slab; in the case of a pitched roof, by the intersection of the elevation wall with the plane corresponding to the extrados of the roof pitch. Unless otherwise specifically prescribed by the individual town-planning instruments, the height measurement does not take into account stairwells, lifts and flues, nor the increases corresponding to basement window wells or external accesses, both vehicular and pedestrian, provided that the accesses themselves, built in a trench with respect to the ground line, are not more than 3 m wide.	
Paragraph n - Maximum height of buildings (HMAX) This is the maximum between the heights of the different parts of the elevation into which the building can be divided, measured as in letter m) above. In the	

case of elevations in which there are inclined roof pitches (gabled, staggered or single-pitched), the maximum height is considered to be that corresponding to the intersection of the elevation walls with the plane corresponding to the extrados of the roof pitch (1) as long as the ridge does not exceed the height measured in this way by more than 1.80 m, otherwise the maximum height is measured at the ridge line (see Figures 1,2,3 and 4). (2) If the roof slopes coincide with the sloping walls of the elevations, the maximum height must always be measured to the ridge line (see Figures 5 and 6). (3) For buildings on land with a natural slope of more than 15%, the maximum height permitted by the town planning instruments, unless more restrictive prescriptions of the same, may be exceeded by 20% in the downstream parts of the elevations, with an absolute maximum of 2.00 (see Figure 7).





Normative clause (*Regolamento edilizio comunale* – Art. 61.2)	Metric phrase	Mark-Up (RASE)	Object needed (building/city model)	Property	Data type	Comparison	Target	Unit	Dependency
In (c) areas of expansion referred to in Article 2 of Ministerial Decree No 1444 of 2 April 1968, published in the Official Gazette of 16 April 1968, No 97 between windowed walls of facing buildings, a minimum distance is prescribed, equal to the height of the tallest building and no lower than 10 m; if the facing facades overlap for more than 12 meters, the rule applies also when only one of them has windows. In the same urban zones the distance of a building from the parcel boundaries shall be equal to the half of the maximum permitted height and in any case not less than 5 m. Construction on parcel boundaries is allowed, where permitted by the urban planning instrument, by agreement between the neighboring owners.	minimum distance	Applycability	- New building - Existing building(s)			Exist			
	(c) areas of expansion	Selection	- Urban zone	Intended Use	Text	=	(c) areas of expansion		
	Between windowed walls of facing buildings	Selection	- New building			Contains	Wall; (which contains) window		If facing walls
			- Existing buidling(s)			Contains	Wall; (which contains) window		
	if facing facades overlap for more than 12 meters, the rule applies also when only one of them has windows	Selection	- New building - Existing building(s)			Contains	Wall; (which contains) window		If walls face each other for at least 12 m
	equal to the height of the tallest building	Requirement	- New building - Existing building(s)	Distance	Number	≥	Building height of the tallest building	m	If Building height of the tallest building is > 10 m
	and no lower than 10	Requirement	- New building - Existing building(s)	Distance	Number	≥	10	m	If Building height of the tallest building is < 10 m
	In the same urban zones, the minimum distance of a building	Applicability	- New building - Parcel			Exist			
	from the parcel boundaries	Selection	- Parcel			Contains	Parcel boundaries		
	shall be equal to the half of the maximum permitted height	Requirement	- New building - Parcel boundaries	Distance	Number	≥	½ of the allowed maximum building height		If ½ of the allowed maximum building height < 5
	and in any case not less than 5 m.	Requirement	- New building - Parcel boundaries	Distance	Number	≥	5	m	If ½ of the allowed maximum building height < 5
	Construction on parcel boundaries is allowed, where permitted by the urban planning instrument, by agreement between the neighboring owners	Exception	- New building - Parcel boundaries	Distance	Number	=	0	m	If a formal consent has been written between (or amongst) the involved parties and it is allowed by urbanistic regulations

Fig. 2: Resulting interpretation of Art. 61.2 based on a semantic mark-up and sentence-centric approach.

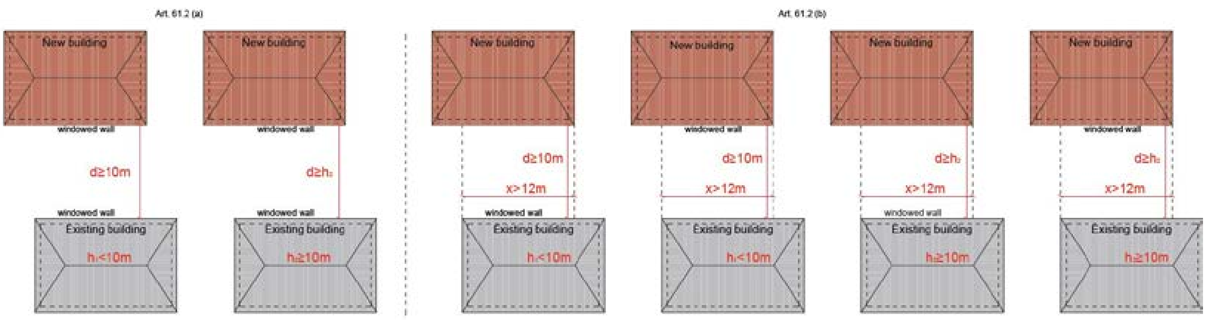


Fig. 3: Graphic Interpretation of Articles 61.2(a) (on the left) and 61.2(b) (on the right).

In the analysis of Article 61.3 shown in Figure 4, there are the values of the distances to be observed in '*other areas*'. This concept was the subject of discussion with the municipality as it does not specify in detail in which Urban Zones it applies. Unlike the previous article, the rule to be respected in this case is that the 3 areas emerged from the comparison: *Historic centre*, *Areas of completion* and *Areas of expansion*.

Normative clause (*Regolamento edilizio comunale* – Art. 61.3)	Metric phrase	Mark-Up (RASE)	Object needed (building/city model)	Property	Data type	Comparison	Target	Unit	Dependency
For all construction operations in other areas, the following minimum distances are prescribed: (1) between windowed walls and walls of buildings in front of which at least one window: ml. 10; (2) from the boundaries: ml.5 and unless otherwise prescribed by the general urban planning instrument.	minimum distance	Applicability	- New building - Existing building(s)			Exist			
	For all construction operations in other areas	Selection	Urban zone	Intended Use	Text	≠	- Historic centre - Areas of completion - Areas of expansion		
	between windowed walls and walls of buildings in front of which at least one window:	Selection	- New building			Contains	Wall: (which contains) window		If facing walls
			- Existing buidling(s)			Contains	Wall: (which contains) window		
	ml. 10	Requirement	- New building - Existing building(s)	Distance	Number	≥	10	m	
	minimum distance	Applicability	- New building - Existing building(s) - Parcel						
	from the boundaries	Selection	- Parcel			Contains	parcel boundaries		
	ml.5	Requirement	- New building - Parcel boundaries	Distance	Number	≥	5	m	
	unless otherwise prescribed by the general urban planning instrument	Exception							

Fig. 4: Resulting interpretation of Art. 61.3 based on a semantic mark-up and sentence-centric approach.

Article 61.4 (Figure 5) deals with the distance that must be between the building and the road. First of all, it is necessary to identify the width of the road. In fact, the article refers to 3 brackets: less than 7 m (1), between 7 m and 15 m (2) and greater than 15 m (3). For these 3 cases it identifies the distance as the sum of the road width increased by a specific value: 5 m for the first case, 7.50 m for the second case and 10 m for the third case. Article 61.6 (Figure 6) deals with the distance between the projecting parts of the building and the parcel boundaries. A requirement emerges that has been identified by the authors as an '*implicit piece of the regulation*'. For the previous articles, the building line from which to calculate the distance referred to the external elevation understood as the external wall that must contain a window (Art.61.2a). In this article, the reference building line is moved from the outer wall to the reference overhang if the latter is less than 1.50 m away from the parcel boundaries. The projections referred to are precisely eaves cornices, open balconies and canopies.

Normative clause (*Regolamento edilizio comunale* – Art. 61.4)	Metric phrase	Mark-Up (RASE)	Object needed (building/city model)	Property	Data type	Comparison	Target	Unit	Dependency
Minimum distance between buildings with roads in-between, excluding cul-de-sac roads serving single buildings or settlements, must be equal to the road width plus: (1) 5.00 m per side, in case of streets width lower than 7.00 m, (2) 7.50 m per side, in case of streets width between 7.00 and 15.00 m, (3) 10.00 m per side, in case of streets width higher than 15.00 m	minimum distance	Applicability	- New building - Existing building(s)			Exist			
	between buildings with roads in-between	Selection	- Road			Exist			If the roads is interposed between New building and Existing building(s)
	excluding cul-de-sac roads serving single buildings or settlements	Exception	- Road	Type	Text	=	Cul-de-sac roads serving individual buildings or settlements		
	in case of streets width lower than 7.00 m	Selection	- Road	Width	Number	<	7	m	
	must be equal to the road width plus 5.00 m per side	Requirement	- New building - Existing building(s)	Distance	Number	≥	Road's width + buffer 5,00 m	m	
	in case of streets width between 7.00 and 15.00 m	Selection	- Road	Width	Number	≥ ≤	7 15	m	
	must be equal to the road width plus 7.50 m per side	Requirement	- New building - Existing building(s)	Distance	Number	≥	Road's width + buffer 7,5 m	m	
	in case of streets width higher than 15.00 m	Selection	- Road	Width	Number	>	15	m	
	must be equal to the road width plus 10.00 m per side	Requirement	- New building - Existing building(s)	Distance	Number	≥	Road's width + buffer 10.00 m	m	

Fig. 5: Resulting interpretation of Art. 61.4 based on a semantic mark-up and sentence-centric approach.

Normative clause (*Regolamento edilizio comunale* – Art. 61.6)	Metric phrase	Mark-Up (RASE)	Object needed (building/city model)	Property	Data type	Comparison	Target	Unit	Dependency
It will not be taken into account for the purposes of determining distances, overhang structures such as steps and open external stairs (maximum height 4). (1) gutter frames, open balconies and canopies, provided that the relative outline remains spaced from the boundaries at least by 1.50 m; (2) While account shall be taken of any body closed in protrusion whatever is the adjective and at whatever height of the building it begins.	distances	Applicability	- New building						
			- Existing building(s)			Exist			
	overhang structures	Selection	- New building - Existing building(s)			Contains	Eave cornices, open balconies and canopies		
	(implicit piece of the regulation)	Requirement	- New building's eave cornices, open balconies and canopies - Existing building(s)	Distance		Must be verified			If not in the exception case (see below)
	It will not be taken into account for the purposes of determining distances, overhang structures such as steps and open external stairs (maximum height 4). (1) gutter frames, open balconies and canopies, provided that the relative outline remains spaced from the boundaries at least by 1.50 m;	Exception	- New building's eave cornices, open balconies and canopies - Existing building(s)	Distance	Number	≥	1,5	m	
	If closed bodies are present in protrusions	Selection	- New building			Contains	Closed building protrusions		
	While account shall be taken of any body closed in protrusion whatever is the adjective and at whatever height of the building it begins.	Requirement	- Building protrusions - Existing building(s)	Distance		Must be verified			

Fig. 6: Resulting interpretation of Art. 61.6 based on a semantic mark-up and sentence-centric approach.

4. INFORMATION REQUIREMENTS DEFINITION

As already mentioned in Section 2.2, Figure 7 shows the representation of the data required to verify the constraints specified in the *Regolamento edilizio comunale* of Ascoli Piceno. Each box represents an entity of building information models or city models, with its specific attributes. To facilitate the identification of entities belonging to the different models, colours were used, assigning a different colour depending on whether the entity should come from a BIM or city model. In particular, *green* was used to identify elements belonging to the building model (BIM) and *blue* to identify elements belonging to the city model (GIS). This distinction allows to have an immediate view of where the data should come from and highlights the necessary correlation between the data of the building and the geospatial data of the urban context in which it is located. This example makes it clear that the need to integrate BIM with GIS, and GIS with BIM, is increasingly essential. A grain size and tolerance must be defined to integrate these two types of data.

Building information models and city models for checking distance-related requirements in a digital building permit use case should contain:

- *urban zones* with an absolute location and for which the *intended use* (e.g., area of expansion; historic centre) is specified;
- *cadastral parcels* with an absolute location and for which *parcel boundaries* are modelled as well;
- *existing buildings*, meaning those that are already located in the urban context of the *buildings* for which the building permit is required. Existing buildings could be detailed with a simplified geometry that allows the extrapolation of the *building height* according to the relevant definition (e.g., a cube for a house with a flat roof that is not accessible). Existing buildings have to contain *windows* to allow building-building distance checks to be executed. Existing buildings have to be identified with their absolute location;
- *buildings*, meaning the ones for which the building permit is required. Buildings need to be detailed with their actual shape and size to identify the building outline. For this reason, buildings need to be modelled including overhangs as *balconies*, *canopies, roofs' eave cornices* and *closed building extrusions*. Appearance is not to be considered for this type of check. Moreover, *external walls* have to include *windows*. The *type of construction* could be a property to assign to buildings (e.g., new construction, renovation) for compliance checking;

- *roads* will have to be modelled including *streets, sidewalks*, *parking spaces* and *flowerbeds*. In fact, according to the definition in Table 2 (see paragraph q), the road is considered as the sum of several elements. The information content of *road* elements has to contain properties as *type of road* (e.g., cul-de-sac) and *width*.

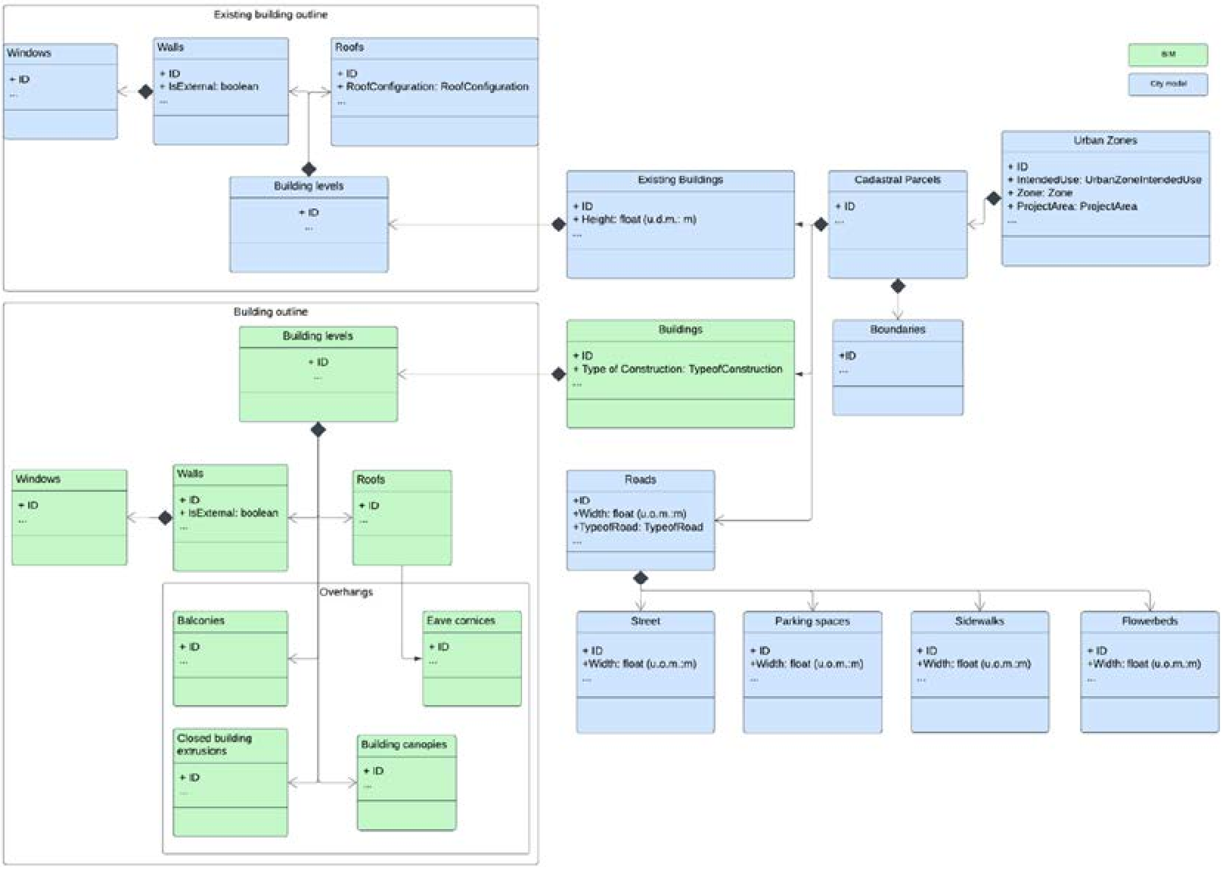


Fig. 7: Conceptual model representing the entities, attributes and relationships that must be present in the model to apply for a digital building permit.

5. CONCLUSIONS

5.1 Discussion of results

This paper describes the interpretation of distance-related regulations for the digitisation of the building permit use case for an Italian municipality of 45.000 inhabitants. Those regulations were selected as a priority by municipality officers, and they check the compliance of design proposal with regulatory requirements related to: building-building distance, building-parcel boundaries distance and building-building distance if a road is interposed. A semantic mark-up and sentence-centric approach has been adopted to extract normative constraints from the natural language of the regulatory text with the aim of translating it into a set of information requirements for the DBP use case. Information requirements have been defined as an essential input to city and building model preparation and they have been formalised in terms of information conceptual models. Domain-specific object types have been associated with required properties properly detailed. Moreover, object types have been matched with a preliminary categorisation into building-related and city-related objects. This could be the basis for the development of standard-oriented specifications for building and city information models.

The rule interpretation step revealed several difficulties, proving to be, as already described in the existing literature, probably the most critical phase in digitising design compliance checking and, specifically, building permitting. First, despite the fact that the municipality officers initially indicated only one regulatory article as necessary for distance verification based on urban zones (i.e., Art. 61 from *Regolamento edilizio comunale*), it was needed to add further regulatory references to this explicit request, either from the same regulatory text or from others normative codes. In addition, it was necessary to interpret not only the regulatory requirements but also the definitions to which they refer (e.g., the actual meaning of building-road distances and maximum building height). Moreover, to validate the extrapolated data and to remove ambiguities related to the complex regulatory textual form, a comparison with municipality officers was essential, which underlines, again confirming the literature, the interpretative subjectivity of building regulations that hardly fits with their digitisation.

5.2 Limitations and future works

Current outcomes show how, despite any fascinating narrative about the automated technical solutions, the hurdles to be tackled with and overcome imply to definitely understand a lot of multi-faceted meanings, unless a whole re-writing of the regulations might be figured out. While the case study is specific in location and regulations, the type of issues encountered are a generally applicable example for the building permit use case. Future works will extend the methodology to the analysis of distance-related regulations from additional three municipalities between 45.000 and 1.000.000 inhabitants, in other two European countries. The resultant level of information need will be formalised in terms of information conceptual models for the complete set of four municipalities and compared to point out the need for a flexible and scalable approach. To this end, the generated data set will be shared with professionals from municipalities, city modellers, and designers to allow the comparison and subsequent validation of the identified and analysed requirements.

Moreover, what is proposed in this article is a first step to proceed, in future works, with deeper analysis in relation to semantics, level of details, geometric representations and GeoBIM interoperability. As a future work, the representation of design and context information according to BIM and geospatial standards will be considered as well as standard definitions for the level of information need as the one proposed by the EN Standard 17412, to be soon re-shaped as a EN ISO Standard.

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6. ACKNOWLEDGEMENT

This research is funded by the Horizon Europe programme of the European Union within the context of the research project *CHEK – Change toolkit for digital building permit* under Grant Agreement No.101058559.

A SYSTEMATIC REVIEW OF THE IMPACTS OF DIGITALIZATION ON PROJECT MANAGEMENT

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ABSTRACT: *This article systematically reviews digitalization's impacts on project management in the construction industry. The article discusses the challenges the construction industry in successfully applying digitalization during the construction phase, including high costs, subpar performance, low productivity, and sustainability issues. The article then outlines the research questions and methodology used to conduct the systematic review, including selecting acceptable research questions, selecting acceptable research questions, using a qualitative approach, and the content review approach. The study analyzed 21 papers and identified the primary research themes regarding the effects of digitalization on project management. The study found that digital technologies, such as smart building technology, digital twins, reality capture, and laser scanning, have positively impacted project management by increasing efficiency, accuracy, value, and safety. The study concludes that the construction industry must embrace digitalization to address its challenges and improve project management.*

KEYWORDS: *Digitalization, Systematic review, Project Management, BIM, Construction Industry,* Automation, Innovation, *Construction Sector*, *Innovation*, *AI*, *Remote, Architect, Engineering*

1. INTRODUCTION

Digitalization is changing the way construction projects are managed and impacting not only the design and construction phases but also facility management (Bazán *et al.,* 2021). It is challenging to successfully apply digitalization during the most time-consuming, expensive, and collaborative period of a project—the construction phase (Qais K. Jahanger *et al.,* 2021). With digitalization being the most promising option to address these difficulties, the construction industry faces a number of hurdles, including high costs, subpar performance, low productivity, and sustainability issues (Nikmehr *et al.,* 2021).

The implementation of Building Information Modelling (BIM) is one of how the construction industry is being digitalized, and its adoption is increasing globally, requiring the conversion of conventional building life cycle phases into BIM-integrated project deliveries (Yilmaz, Akcamete and Demirors, 2023). Strong relationships between frequently encountered independent BIM uses are a requirement for the Total BIM approach, where the principal contractual and legally binding construction document should be production-oriented BIM. Other key success elements include cloud-based model administration, user-friendly on-site mobile BIM software, and strong leadership (Disney *et al.,* 2022). However, BIM deployment frequently has limitations, such as parallel 2D drawing production, which results in wasteful effort, and the need for structural engineers on-site to develop POVs for construction because collecting measurements using the software was not supported. Additionally, Tekla, which supports a 3D model-based approach for rebar and steel structures, is used in the examples, which largely focus on infrastructure projects (Disney *et al.,* 2022).

To fully utilize BIM and digitalization in project management, it is necessary to develop tools for documentation, registration, and data management that allow for effective information sharing among all stakeholders (Bazán *et al*., 2021). Moreover, the cost of construction expert's services, including BIM services, which are now determined by established rates based on construction and equipment prices, can be more accurately predicted with the help of historical data (Nguyen, Dang and Nguyen, 2022). Using BIM-Facility Management with three-dimensional information models created during construction, BIM-based solutions offer the opportunity for collaborative, multidisciplinary workflows and full life cycle consideration (Bazán *et al*., 2021).

Apart from BIM, the construction industry is also moving towards Construction Automation and Robotics (CAR) (Pons-Valladares *et al*., 2023). This is because the upkeep and building of conventional structures account for roughly 30-40% of global energy usage and greenhouse gas emissions into the built environment, posing a threat to the environment due to the significant amount of resources and energy required in these buildings (Ejidike and Mewomo, 2023). According to the UN, the construction industry is responsible for around 40% of global energy use, nearly 40% of waste production, and roughly 30% of greenhouse gas emissions related to energy (Reinbold *et al.*, 2022).

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Ailin Zerafat, Emmanuel Daniel, Louis Gyoh, *A Systematic Review of the Impacts of Digitalization on Project Management,* pp. 538-544, DOI 10.36253/979-12-215-0289-3.52

As part of industrial digitalization, the manufacturing sector makes use of digital technologies like AI, cloud processing, and IoT. This speaks of initiatives taken to increase output using digital technology, which can have an effect on all areas of an organization and alter current business procedures (Carlsson, 2023). Effective strategizing of organizational capabilities relies on managers' capacity to elucidate the socio-cognitive factors, and it contributes to management practice by highlighting the divergent opinions among managers concerning digital technology's influence on efforts to improve the organization (Carlsson, 2023). Additionally, a potential solution to the lack of focus on workers in digitalization research for the construction industry is digital visual management (DVM), which aims to provide real-time visual information that can be easily accessed and utilized during production activities to increase transparency and communication. However, understanding the various actors' information needs is crucial to effectively implement DVM (Reinbold *et al.*, 2022).

The growth of digital methods is transforming the design and construction business, impacting not only how the sector operates but also the range of output; yet, there is a dearth of critical analysis because the majority of research mainly concentrate on creating the approaches (Brooks, Zantinge and Elghaish, 2022). The lack of comprehensive analysis of this disaggregated knowledge on the application of digital technology in project management informed the current systematic literature review. This study aimed to comprehend how digitalization has affected project management. The study objectives are;

• To examine the project management literature currently available on digitalization.

• To determine how project management is currently using digitalization.

• To identify the obstacles preventing the use of digitization in project management

The building industry faces the challenge of creating comprehensively built infrastructures that meet the demands of a growing population, urban sprawl, and globalization. This includes implementing efficient energy management, ensuring proper water supply, providing indoor comfort for occupants, and managing construction waste (Ejidike and Mewomo, 2023). The substantial financial burden of maintaining and repairing deteriorating facilities is highlighted by the necessity for improved management and inspection systems given the size of some countries' infrastructure (Bazán *et al*., 2021). The successful use of digital technology by a construction company depends on having sufficient knowledge of the organization, including its structure, nature of work, and human resource characteristics (Nikmehr *et al.,* 2021).

2. RESEARCH METHOD

The basis for increasing knowledge in a certain discipline, such as architecture and construction, among others, is a thorough review of the scientific literature. The study employed a systematic review methodology, in accordance with the strategy described by Denyer and Tranfield, to thoroughly assess the body of literature and arrange knowledge into a trustworthy manner that can influence practices (Ejidike and Mewomo, 2023).

This literature review with a qualitative approach aims to explore the advantages of digitalization in project management in the construction industry. The review employs the Scopus search engine to locate pertinent papers. Due to Scopus's high data recovery accuracy and precision, the researcher chose to use it for their literature search. The investigation considers papers published between 2015 and 2022, using the following search strategy: (TITLE-ABS-KEY ("Digitalization" AND Construction AND Management)).

The initial search resulted in 129 articles that met the criteria. Inclusion and exclusion criteria were applied to ensure that only relevant papers were selected. The criteria stipulated that the articles must be in English and deal with engineering. Any papers that did not meet these criteria were discarded. The review specifically focused on digitalization in project management, analyzing pertinent academic journals and conference papers. Despite the thorough search, not all of the articles that were found appeared to be pertinent to the study's specific focus. Therefore, the researcher used a content review approach to further filter and select the most relevant papers for the investigation.

The content review approach involved a three-step process. First, the researcher examined the article's topical relevance to the study. Second, the researcher analyzed the abstract to determine whether the article provided sufficient information related to the study's focus. Finally, the researcher reviewed the article's findings as they were reported in the literature. After applying the content review approach, a total of 21 papers were selected for examination. These papers were analyzed in detail, and their findings were synthesized to develop a comprehensive understanding of the advantages of digitalization in project management in the construction industry.

To ensure the reliability of the literature review, the researcher used a systematic approach to the search, screening, and selection of articles(citation). The inclusion and exclusion criteria were clearly defined and consistently applied throughout the study. The content review approach provided a structured and transparent method for selecting the most relevant papers for the investigation.

The primary research themes regarding the effects of digitalization on project management were identified and categorised in this study, with the hopes that the findings will help other researchers better understand current events, trends, and potential areas for research and innovation in the AEC industry.

3. RESULT AND DISCUSSION

3.1 Qualitative Analysis and Discussion

3.1.1 The state-of-art of Digitalization in project management

Digitalization in project management is a growing trend that is transforming the Architecture, Engineering, Construction, and Facility Management (AEC-FM) sector in many ways. Digital technologies, such as IoT, UAVs, 3D printing, AR, VR, MR, BIM, AI, and DSS, are increasingly being used to solve problems with cost, rework, efficiency, safety, quality, and productivity (Nikmehr et al., 2021). Web-based project systems, digital meetings, and BIM have been available for some time, but they are not always fully utilized. However, the right digitalization approach can reverse productivity declines, and European Directives for Procurement are pushing for more radical digital transformations with support for R&D and training (Prebanić and Vukomanović, 2021).

Project managers are responsible for determining how to use ICT tools to involve project stakeholders effectively, and there is extensive research on the digitalization of construction project management practices (Prebanić and Vukomanović, 2021). Digital technology has been used in the construction industry in the past, but its scope was limited due to technological constraints. However, advancements in processing power have given construction organizations the opportunity to combine their skills and enhance their processes using digital technology (Lundberg, Nylén and Sandberg, 2022).

Digital twins, which are virtual replicas of physical things that faithfully reproduce all of their properties, including how they behave under actual use-case scenarios, can aid in the integration of various information technologies into a single digital platform and twin for construction projects (Ryzhakova *et al.,* 2022). Reality Capture (RC), a valuable tool for construction project management, can increase project efficiency, correctness, value, and safety by incorporating building geometry, build typology, and material amounts in 3D models (Fobiri, Musonda and Muleya, 2022). Similarly, laser scanning, which is safe and non-invasive and efficiently and precisely organizes space, is gaining popularity in the fields of design, engineering, and construction, all of which contribute to the achievement of sustainable development goals (Fobiri, Musonda and Muleya, 2022). Digital technologies are having an increasingly negative impact on the AEC-FM sector in two ways: the monitoring of sensor network data and the easy management of automation systems (Hosamo *et al.,* 2022).

Both industrialized and developing countries have adopted sustainable construction techniques, such as green roofs and structures, modular construction, information modeling, and smart building technology (SBT), to improve their processes (Ejidike and Mewomo, 2023).

3.1.2 The impacts of Digitalization in project management

As technology has advanced, building experts have increasingly used it to improve energy management, environmental protection, economic efficiency, and human comfort (Ejidike and Mewomo, 2023). By encouraging sustainable construction methods that limit waste output, maximize resource consumption, and minimize environmental effect, smart building technology adoption benefits professionals, clients, and the nation as a whole in developing countries (Ejidike and Mewomo, 2023). For the purpose of enhancing and facilitating a specific activity, new digital technologies like computer modeling, digitalization, and creative business processes are being developed (Brooks, Zantinge and Elghaish, 2022).

Digitalization has the ability to improve project management and delivery through the use of construction or document software solutions, which includes contractor, document management, process management, and activity monitoring and oversight (Qais K. Jahanger *et al.,* 2021). A construction company must have a strong commitment to change in order to achieve real digital transformation, as opposed to running analogue and digital systems in parallel. It also needs to develop and implement a defined digitalization transition strategy (Nikmehr *et* *al.,* 2021). BIM and other digital technologies have been utilized successfully in construction projects all around the world, showcasing their capacity to manage multidisciplinary teams, spot conflicts, and minimize rework in significant projects (Nikmehr *et al.,* 2021).

The development of 3D models made possible by the application of RC technologies in construction management provides clients, consultants, and contractors with a singular learning chance to interact with and define faults, structural analyses, constructability challenges, risks, and costs in real-time, in a secure, hazard-free environment (Fobiri, Musonda and Muleya, 2022). Although Big Data technology can assist with analysis and processing of the large and complex datasets created by construction projects, it is still difficult to integrate data from various automated systems to create a digital twin (Ryzhakova *et al.,* 2022). The Digital Twin can interact with other simulators and programs by incorporating data and information from throughout an asset's existence, making it a crucial decision-making tool for the duration of the asset (Hosamo *et al.,* 2022).

In order to meet market demand and improve their value offer, the UK's changing construction agenda is encouraging construction companies to adopt new business models that make use of digital technology and manufacturing processes to develop and deliver whole life value (Çıdık and Boyd, 2022). The construction industry's methods for generating and capturing value change as a result of digitalization, which causes a transition from project-based logic to production-based logic (Çıdık and Boyd, 2022). The construction industry's interdisciplinary, dispersed, and temporary project organizations, as well as the interdependencies between stakeholders, add complexity and make it difficult to meet project requirements for cost, time, and productivity. This calls for improved integration, cooperation, interaction, and coordination (Prebanić and Vukomanović, 2021).

3.1.3 How Digitalization impacts on Project Management

The push for digitization in construction highlights the need for change in the way construction is planned and carried out (Brooks, Zantinge and Elghaish, 2022). Digitalization in construction practices uses digital technologies to create new organizational practices (Lundberg, Nylén and Sandberg, 2022). A digital representation of the real world can be made using Reality Capture (RC) technology, making it easier to plan, oversee, and evaluate construction, engineering, and architectural projects (Fobiri, Musonda and Muleya, 2022). The use of digital models of buildings and planned project activities can support tasks at different levels, such as transaction conclusion, securing investment support, and thorough assessments of capital construction objects (Ekaterina Tereshko, 2021). Building assets must be managed, and facility management (FM) calls for handling a lot of data, which is currently kept in paper documents that are prone to theft (Siccardi and Villa, 2023).

Through the seamless integration of information using information-based systems like Building Information Modeling (BIM), AEC-FM operations can be improved, projects can be more efficiently completed, and their efficacy over their whole lifespan can be increased (Hosamo *et al.,* 2022). Throughout the entire building construction process, risk prevention and safety planning have advanced significantly thanks to the use of BIM methods and digital twins, which enable accurate data collection and 3D visualization (Torrecilla-García, J., Pardo-Ferreira, M., Rubio-Romero,J., 2021). A technology was created to build and analyse models of control processes as well as create strategies and tactics to apply the findings to real-world demands (Ereshko *et al.,* 2022). Digital construction-phase information management (DCIM) systems can be an effective solution for reversing the fall in productivity in the construction industry, however certain governmental agencies have not yet completely adopted this technology (Qais K. Jahanger *et al.,* 2021). An information system with an intuitive design and standardized methods for data extraction, transformation, and loading can guarantee the long-term archiving, updating, and synchronization of metadata and data from different information systems while also safeguarding it from unauthorized access by other project participants (Ryzhakova *et al.,* 2022).

Convenience, cost savings, a wider range of options, greater information, improved sustainability, higher communication quality, increased customer satisfaction, and success of economic models and investments are just a few of the advantages that digitalization brings to industries (Nikmehr *et al.,* 2021). The construction industry's interdisciplinary, dispersed, and temporary project organizations, as well as the interdependencies between stakeholders, add complexity and make it difficult to meet project requirements for cost, time, and productivity. This calls for improved integration, cooperation, interaction, and coordination (Prebanić and Vukomanović, 2021). Because of the intricate nature of projects and the involvement of several contracting parties with potentially competing interests, stakeholder management, which includes stakeholder analysis and engagement, is essential in the construction industry (Prebanić and Vukomanović, 2021).

To ensure the adoption of smart building technology in underdeveloped countries, it is essential to fully comprehend its benefits, make the concept more familiar to building experts, and promote its successful use in those areas (Ejidike and Mewomo, 2023). The current emphasis on digitization in the agenda for transforming construction assumes that integrated digital technologies can identify coordination issues and enable better inter-organizational cooperation, but this perspective poorly articulates how value is formed and ignores the practical difficulties of digitization (Çıdık and Boyd, 2022).

4. RECOMMENDATIONS AND DIRECTIONS FOR FUTURE RESEARCH

Digital technologies have disrupted many industries, and project management is no exception. Digitalization has enabled project managers to leverage new tools and techniques to improve project outcomes and collaboration, but it has also brought new challenges related to data privacy, security, and governance. To address these challenges and leverage the benefits of digitalization, there is a need for further research in the impacts of digitalization in project management. This article provides recommendations and directions for future research in this field.

The first recommendation is to investigate the adoption rate of digital technologies in project management and identify factors influencing its adoption. This research can provide insights into the current state-of-art of digitalization in project management and help project managers understand the factors that drive or hinder its adoption. For example, research could explore the impact of organizational culture, leadership support, and digital competencies on adopting digital technologies in project management.

The second recommendation is to examine the role of digital technologies in enabling remote project management and explore the impact on team collaboration and communication. With the rise of remote work, project managers need to adapt to new ways of working and leverage digital technologies to collaborate effectively with team members who are geographically dispersed. Research could explore the impact of digital tools such as video conferencing, instant messaging, and collaboration platforms on team communication, collaboration, and performance.

The third recommendation is to analyze the impact of digitalization on project outcomes, including project completion time, cost, quality, and scope. Digital technologies can potentially improve project outcomes by enabling more efficient and effective project planning, execution, monitoring, and control. However, research is needed to understand the specific impact of digital technologies on different project outcomes and to identify best practices for leveraging digital technologies to improve project outcomes.

The fourth recommendation is to investigate the impact of digital technologies on project risk management, including identifying, assessing, and mitigating risks. Digital technologies can enable more effective risk management by providing project managers with real-time data and insights into project risks. Research could explore the impact of digital tools such as risk management software, predictive analytics, and machine learning on project risk management and identify best practices for leveraging these tools to mitigate project risks.

The fifth recommendation is to explore the impact of digitalization on project management processes, including project planning, execution, monitoring, and control. Digital technologies can enable more efficient and effective project management processes by automating tasks, providing real-time data, and enabling more effective collaboration. Research could explore the impact of digital tools such as project management software, project management dashboards, and agile methodologies on project management processes and identify best practices for leveraging these tools to improve project management processes.

5. CONCLUSION

In this systematic review, the aim was to investigate the impacts of digitalization on project management in the construction industry. The study revealed both the challenges faced during the implementation of digitalization, such as high costs and sustainability issues, and the positive outcomes resulting from the adoption of digital technologies. Through a comprehensive analysis of 21 papers, the study identified key research themes highlighting the transformative potential of digital tools like smart building technology, digital twins, reality capture, and laser scanning. These technologies have proven to enhance project management by increasing efficiency, accuracy, value, and safety.

The findings emphasize the need for the construction industry to fully embrace digitalization. Integrating Building Information Modelling (BIM) and other digital tools facilitates effective information sharing, enabling collaborative and multidisciplinary workflows throughout the construction lifecycle. Additionally, Construction Automation and Robotics (CAR) are emerging as essential components in sustainable construction practices. To successfully leverage digitalization, organizations must adopt a defined digitalization transition strategy and genuinely commit to a digital transformation, considering the organization's structure, nature of work, and human resource characteristics.

Looking ahead, further research is recommended to explore the adoption rate of digital technologies in project management and the factors influencing their successful implementation. Understanding the role of digital technologies in enabling remote project management and their impact on team collaboration and communication is crucial in adapting to evolving work practices. Moreover, in-depth analysis of the impact of digitalization on project outcomes, risk management, and project management processes will provide valuable insights and best practices for the industry. Ultimately, embracing digitalization presents not only a necessity but also an opportunity for the construction industry to thrive in an increasingly digital world, delivering successful projects that meet the demands of a growing population and sustainability requirements.

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EVALUATING THE COMPREHENSION OF CONSTRUCTION SCHEDULES OF AN ARTIFICIAL INTELLIGENCE

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ABSTRACT: *Construction schedules are an important tool to communicate with the project stakeholders and are critical for the project management team to plan, coordinate, and manage construction projects. Each construction project has a unique schedule that is created based on the construction drawings, specifications, contracting requirements, construction methods, and the judgment of the project management team. Therefore, each construction schedule is unique in many aspects such as the number of activities, the names of the activities, the duration of those activities, and the relationship between the activities. The names of the activities are of particular interest as they are the critical core unit to creating the schedule. Furthermore, the activities are the ones that bring together all other aspects of the schedule. Unfortunately, there is no standard naming conversion for those activities and they vary from project to project as well as from project management team to project management team. This inconsistency of the activity name makes it extremely challenging for both humans and machines to understand the meaning and scope of the activities. Thus, the problem that this paper addresses is the challenge faced by machines to comprehend the activities of a construction schedule. Therefore, the objective of this paper is to evaluate the ability of an Artificial Intelligence (AI) implementation to comprehend activities in a construction schedule. This research was conducted following a mixed research method. The AI implementation training was done by providing the Construction Specifications Institute (CSI) Master Format activity list to a Sentence Transformer. Then the AI was given the task of interpreting the activities of a construction schedule according to the 50 Divisions of the CSI Master Format. A group of senior construction students was also given the same interpretation task. The evaluation was done by comparing the results of the AI vs the humans for each of the activities in the construction schedule. The result was that the AI has 0.56 accuracy, 0.50 precision, 0.85 recall and, 0.64 F1 Score. This result is very promising and it supports further research to refine the AI to increase its ability to comprehend construction schedule activities. Upon achieving a higher level of comprehension an AI could be used to assist humans in the preparation of construction schedules or perhaps prepare drafts of the construction schedules for the human to review.*

KEYWORDS: *Construction Scheduling, Decision Support, Artificial Intelligence, Comprehension*

1. BACKGROUND

Construction scheduling is a complex process with a lot of considerations for successful project delivery with different and specific approaches for each scheduling constraint (Okonkwo et al., 2022). Preparing good schedules is a time-consuming process that requires a deep understanding of the construction process (Sulbaran, & Ahmed, 2017). Construction schedules serve many purposes ranging from informing owners on state of progress, establishing long-term coordination among crews and trade contractors, to specifying terms of payment (Halpin & Senior, Bolivar, 2017). The construction schedule is one of the most important planning and control tools for the construction process (Rosłon et al., 2020), frequently includes a very large number of activities (Essam et al., 2023) and it is the core of the project plan. It is used by the project management team to commit resources to the project and show the organization how the work will be performed (Magalhães-Mendes, 2011). The main goal of a construction schedule is to identify the activities needed to complete a project and sequence them in the most efficient way possible within the timeframe and resources available (Essam et al., 2023). Construction scheduling is a complex process due to the interdependence and contradiction of project activities (Essam et al., 2023). Construction schedule practices rely heavily on manually elaborated descriptions of construction means and methods (Amer & Golparvar-Fard, 2019). The preparation of a construction schedule including the number of activities, the names of the activities, the duration of those activities, and the relationship between the activities which heavily relies on the judgment and expertise of the project management team.

The names of the construction activities are the only unstructured data attribute in the construction schedules (Hong et al., 2021). Construction activities are described using Natural Language expressions with little or no standardization, grammatical errors, abbreviations, project and construction-specific terms (Heigermoser et al., 2019). Construction activities have been widely discussed in the construction literature (Amer & Golparvar-Fard, 2019) as they are critical in construction schedules. The activity names are devised to communicate between stakeholders, however, they are often written using inconsistent terminologies with omitted contextual information

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Tulio Sulbaran, *Evaluating the Comprehension of Construction Schedules of an Artificial Intelligence,* pp. 545-552,
DOI 10.36253/979-12-215-0289-3.53

(Hong et al., 2021). The inconsistency and omissions are due in part because construction schedules are prepared by project management teams' using their tacit knowledge. The tacit knowledge is the common knowledge on the process of conformance checking that is applied by domain experts (Yurchyshyna & Zarli, 2009). This inconsistency in the activity names is further aggravated by the variety of construction means and methods to perform construction activities and the differences in practice between different construction companies (Amer & Golparvar-Fard, 2019). It is also the case that in most instances, historic information including scheduling decision reasoning is not documented and disseminated for use in other future projects (Hong et al., 2022). Although construction companies might establish procedures to propagate their construction scheduling knowledge between different projects and teams (Amer & Golparvar-Fard, 2019), it is ultimately the project management team that prepares the construction schedule. This current scheduling practice leads to activities written in an inconsistent format with inconsistent terminologies (Hong et al., 2021) which makes it extremely challenging for both humans and machines to understand the meaning and scope of the activities.

The problem addressed by this paper is the challenge faced by machines to comprehend the activities of a construction schedule. Thus, the objective of this paper is to evaluate the ability of an Artificial Intelligence (AI) implementation to comprehend activities of a construction schedule. The AI's ability to comprehend construction activities is critical to further advance the AI competence to assist project management team in the preparation of construction schedules or perhaps prepare drafts of the construction schedules for them to review and fine tune.

Artificial intelligence (AI) is poised to rapidly transform businesses particularly the construction industry. Although, AI is still a new technology in the construction industry, it has the potential to have a major impact particularly in construction schedules. AI powered scheduling tools could help the project management teams create more accurate and efficient schedules, which could lead to significant cost savings and time savings. Optimized schedules are expected to yield significant cost savings over the actual schedules employed (Kettunen & Kwak, 2018).

Artificial Intelligence has many branches and sub-branches as shown in Figure 1. Artificial Intelligence is the capability of a device to perform functions that are normally associated with human intelligence, such as reasoning and optimization through experience (Grewal, 2014). Artificial intelligence brings into being machines that respond to stimulation consistent with traditional responses from humans, given the human capacity for contemplation, judgment and intention (Grewal, 2014).

A subset of Artificial Intelligence (AI) is Machine Learning (ML) in which intelligence is provided to a system so that it can act automatically make decisions depending on the past experiences (Tiwari, 2022). Machine learning focuses on the development of algorithms that can learn from data without being explicitly programmed. ML algorithms are typically trained on large datasets of labeled data, and they can then be used to make predictions or decisions on new data. One of the types of machine learning is unsupervised learning in which the algorithm is not given any labeled data. Instead, the algorithm is given unlabeled data and it must find patterns in the data on its own. Unsupervised learning algorithms try to infer a function to find hidden relations between data points (Tiwari, 2022).

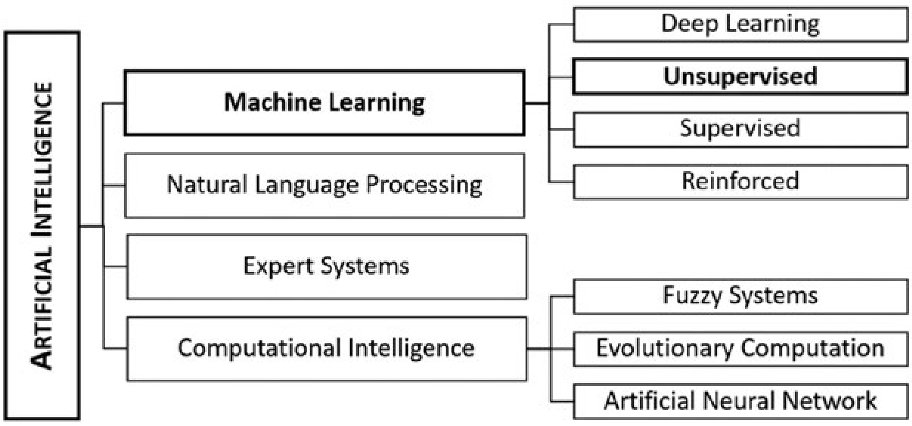

Fig. 1: Sample Areas of Artificial Intelligence

2. RESEARCH METHODOLOGY

A mixed research method was used in this research. The mixed research method draws largely on quantitative and qualitative research (Leedy et al., 2019). Despite its advantages in comparison to mono methods, mixed methods research had been underutilized in the management sciences (Molina-Azorin & Cameron, 2010). However today, mixed methods research is increasingly being used in many disciplines (Bentahar & Cameron, 2015). The use of mixed research method has increased so much that a specialized journal is devoted specifically to mixed methods research - The Journal of Mixed Methods Research, published by Sage (Bentahar & Cameron, 2015). The mixed method was used in this research because both non-numerical and numerical data were needed to evaluate the ability of an AI implementation to comprehend activities of construction schedules. The implementation of the mixed research method was done in four stages: data collection, AI training and preparation, activity interpretation, and analysis as shown in Figure 2.

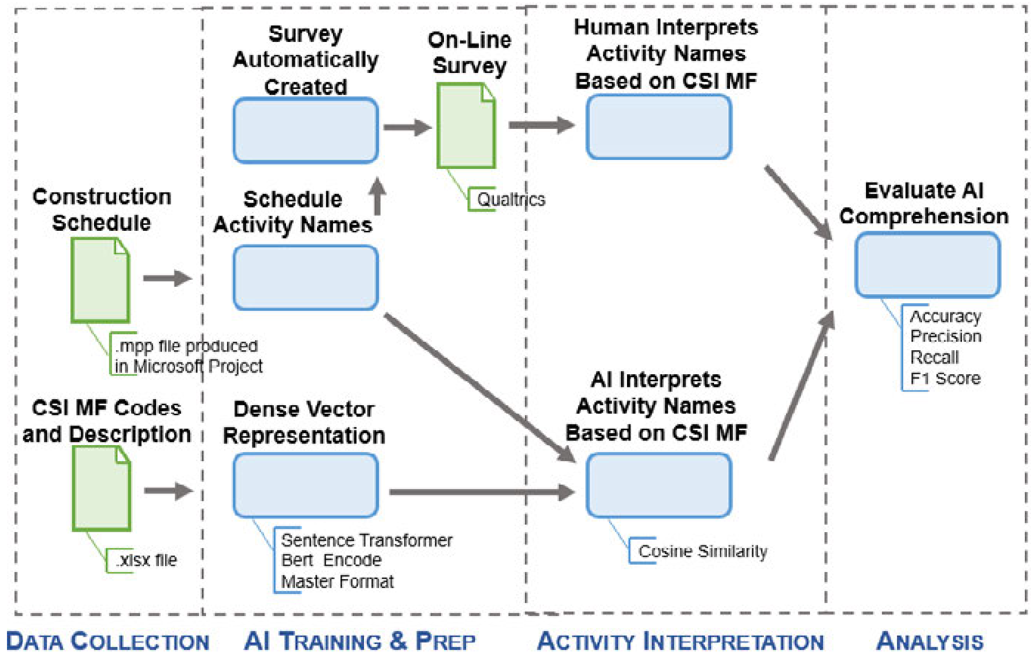

Figure 2: Research Stages

- *Data Collection:* data of a construction schedule as well as data regarding the Construction Specifications Institute (CSI) Master Format (MF) 50 divisions activity codes and descriptions were gathered.

- *Artificial Intelligence Training and Preparation:* the CSI MF 50 divisions activity codes and descriptions were used to train the machine using sentence transformer with a BERT encoder. During the stage also the activities from the construction schedule were extracted and used to automatically create the question of a survey to be deployed on-line through Qualtrics.

- *Activity Interpretation:* the activities of the schedule were provided to a group of humans and an AI. They both were asked to interpret the activities in accordance to the CSI MF 50 divisions. The humans completed the tasks through the online-survey in Qualtrics while the AI completed using the cosine similarity metric.

- *Analysis:* confusion matrix was used to evaluate the AI comprehension of activities in the construction schedule including four metrics – accuracy, precision, recall, and F1 scores to provide a complete picture of the AI performance.

3. RESULTS

3.1 Data Collection

The construction schedule gathered for this research project was composed of 94 activities from notice to proceed to final completion. The project was a 6,500 SF, single story, steel frame, metal stud, gypsum partitions with loadbearing brick and block. The project was a court house in a city in the United States with an approximate cost of $300/SF and a total estimated cost of approximately 2 million dollars.

The Construction Specifications Institute (CSI) Master Format (MF) 50 divisions activity codes and descriptions gathered for this project were composed 7533 individual activities grouped in 35 divisions currently activity from Division 00 – Procurement and Contracting Requirements to Division 48 – Electrical Power Generation.

3.2 Artificial Intelligence Training and Preparation

The training of Artificial Intelligence (AI) was done in Jupyter Notebook which is a free, open-source, interactive web tool known as a computational notebook (Perkel, 2018). Jupyter Notebook was used because it has emerged as a de facto standard for data scientists (Perkel, 2018). The programming code in Jupyter Notebook was done using Python taking advantage of the Sentence Transformers framework to compute semantic similarity and develop the embedding model (Devika et al., 2021). An embedding model is a type of machine learning model that is used to represent words or other discrete entities as real-valued vectors. The real-valued vectors were created using the Bidirectional Encoder Representation Transformers (BERT) Natural Language Inference (NLI) which maps sentences & paragraphs to a 768-dimensional dense vector space and can be used for tasks like clustering or semantic search (Devika et al., 2021). The BERT-NLI models was provided the list of the Construction Specifications Institute (CSI) Master Format (MF) 50 divisions activity codes and returned the corresponding vector for each of the 50 divisions.

The preparation of the survey was done by uploading the construction schedule into a Jupyter Notebook. The Jupyter Notebook extracted the 94 activities from the construction schedule and automatically prepared the 94 questions using the template shown in the Table 1a. Additionally, the questions were grouped into four quartiles according to the cosine of similarity values between the activity and the CSI MF 50 Divisions per the AI Interpretation of the Activities as shown in Table 1b. The four group of questions were uploaded into Qualtrics. In Qualtrics, randomized sub-set of questions to be shown to each participant from each quartile were entered as shown Table 2.

Table 1: Template, Quartiles, and Number of Questions

a. Questions Template
Activity Description: <Activity from Construction Schedule Here> Select from the pulldown below the CSI Master Format Division for which the activity description above (in bold) belongs to. If the activity does NOT belong to any of the CSI Master Format select "None of the Above".

b. Quartile and Number of Questions

Quartiles	**Cos Similarity Values**	**Number of Activities**
Top 25%	More than 0.875	24
Second 25%	0.875 to 0.831	23
Third 25%	0.830 to 0.779	23
Bottom 25	Less than 0.779	24

3.3 Schedule Activity Interpretation

The first part of the construction schedule activity interpretation was done by humans. To ensure that the participating humans could answer the questions within 15 minutes, only the randomized sub-set of questions were provided to each participating human. The sub-sets were composed of 18 of the 94 questions. In the 18 questions, there were three questions from the top two quartiles and six questions from the bottom two quartiles as shown in Table 2. This decision of having more questions from the bottom two quartiles was done because it was anticipated that there was going to be a lower percentage of AI construction activity interpretation that were going to match the interpretation from the participants. Additionally, none of the questions were mandatory, so the participants could skip some of the questions resulting in a total of 316 answers from the participants. The second part of the construction schedule activity interpretation was done by AI using the BERT-NLI model. The AI was given the same construction schedule activities with the same questions given to the human.

Table 2: Questions Template and Number

Quartiles	Questions Per participant	Total Questions Answered
Top 25%	3	51
Second 25%	3	53
Third 25%	6	105
Bottom 25%	6	107
Total	18	316

3.4 Artificial Intelligence Schedule Activity Analysis

The task of interpreting the activities of a construction schedule according to the 50 Divisions of the CSI Master Format was completed first by eighteen human participants. The participants' demographic was as follows: 77.8% Hispanics, 61.1% between 20 and 24 years old, 77.8% males, and 55.6% with 1 to 5 years work experience. The responses of the participants were grouped in the same four quartiles of questions as shown in Table 1 then the answers of the AI were also grouped in according to the four quartiles. If the answer of the AI matched the answer of the humans, the answer was considered a match if not it was considered a no match. The AI identification of the activities match the human answer on average 50% for the first the three quartiles which correspond to the quartiles that the AI was expected to match the human answer. Likewise, the AI identified activities did not match the human answer in the bottom quartile 75% of the times as expected.

Table 3. Questions Template and Number

Quartiles	Number of Activities	Number and % of Match	Number and % of No match	Number and % of Match	Number and % of No match
Top 25%	24	14 (58.3%)	10 (41.7%)	35 (50.0%)	35 (50.0%)
Second 25%	23	10 (43.5%)	13 (56.5%)		
Third 25%	23	11 (47.8%)	12 (52.2%)		
Bottom 25%	24	6 (25.0%)	18 (75.0%)	6 (25.0%)	18 (75.0%)

Furthermore, the Artificial Intelligence (AI) comprehension of the scheduling activities was also done using a confusion matrix. A confusion matrix represents the prediction summary in matrix form (Tiwari, 2022). It is a tool to determine the performance of the AI useful to identify areas where the AI may need improvement. The confusion matrix is useful because shows how many predictions are correct (true) and incorrect (false) per class (Tiwari, 2022). The two classes used in this research were that the AI was either expected to identify (top three quartile) or no identify (bottom quartile) the activities in the construction schedule.

The values used in the confusion matrix for the AI Activity interpretation correspond to the first top three quartiles for identified and the bottom quartile for the not identified. Also, for the actual activity identified corresponds to the match while the not identified correspond to the no match. As shown in Figure 3, the confusion matrix has two rows and two columns with four possible outcomes (true positive, false negative, false positive, and true negative). The top left quadrant shows the number of true positives, which are cases where the AI implementation correctly identified the activity. The bottom left quadrant shows the number of false negatives (also known as type II error), which are cases where the AI implementation was not expected to identify the activity but was in fact able to identify the activity. The top right quadrant shows the number of false positives (also known as type I error), which are cases where the AI implementation was expected to identify the activity, but provided the wrong activity interpretation. The bottom right quadrant shows the number of true negatives, which are cases where the AI implementation was not expected to identify the activity and in fact was not able to identify the activity.

AI Activity Interpretation	Actual Activity: Identified	Actual Activity: Not Identified
Identified	True (1) Positive (TP) 35	False (2) Positive (FP) 35
Not Identified	False (3) Negative (FN) 6	True (1) Negatives (TN) 18

Legend:

AI was expected to identify activities

TP = True Positive = AI correctly identified activity (as expected)

FP = False Positive = AI did not identify activity

AI was not expected to identify activities

FN = False Negative = AI correctly identify activity (although it was not expected to identify the activity)

TN = True Negatives = AI did not identify activity (as expected)

(1) Correct predictions

(2) Type I Error

(3) Type II Error

Figure 3: AI Interpretation of Construction Activities Confusion Matrix

The confusion matrix information was used to calculate four metrics – accuracy, precision, recall, and F1 scores to provide a complete picture of the AI performance in comprehending the activities in the construction schedule.

- *Accuracy:* is used to find the portion of correctly interpreted activities. In other words, measures how often the AI is correct. The value ranges from 1 for 100% accurate to 0 for 0% accurate. The equation used to calculate accuracy is presented in Equation 1 resulting in the AI having an accuracy to identify activities of 0.56.

$$Accuracy = \frac{TP+TN}{TP+TN+FP+FN} = \frac{35+18}{35+18+35+6} = 0.56 \qquad \text{Equation 1}$$

- *Precision:* is used to calculate the AI's ability to interpret positive values correctly (True). In other words, measures how often the AI correctly identified the activity when it was expected to do so. Precision is equal to the ratio of the number of construction activities correctly interpreted to the total number of construction activities predicted. The value ranges from 1 for 100% precise to 0 for 0% precision. The equation used to calculate precision is presented in Equation 2 resulting in the AI having a precision to identify activities of 0.50. This result is consistent with literature as fully AI automated approach is still immature to be used in the industry where the best model scored 0.511 precision (Amer et al., 2021)

$$Precision = \frac{TP}{TP+FP} = \frac{35}{35+35} = 0.50 \qquad \text{Equation 2}$$

- *Recall:* (also called sensitivity) is used to calculate the AI's ability to interpret activities among all the activities. In other words, measures how often do the AI correctly identified the activities weather or not is expected to do so. Recall is the ratio of the number of construction activities correctly interpreted to the total number of construction activities interpreted. The value ranges from 1 for 100% recall to 0 for 0% recall. The equation used to calculate precision is presented in Equation 3 resulting in the AI having a recall to identify activities of 0.85.

$$Recall = \frac{TP}{TP+FN} = \frac{35}{35+6} = 0.85 \qquad \text{Equation 3}$$

-*F1-Score:* is the harmonic mean of Recall and Precision. In other words, it is useful when a balance between Precision and Recall needs to be taken into account.

$$F1\ Score = \frac{2*Precision*Recall}{Precision+Recall} = \frac{2*0.50*0.85}{0.50+0.85} = 0.63 \qquad \text{Equation 4}$$

4. SUMMARY

The construction schedule activity names are of particular interest as they are the critical core unit to create the schedule. Unfortunately, there is no standard naming conversion for those activities and they vary from project to project as well as from project management team to project management team. This inconsistency of the activity name makes it extremely challenging for both humans and machines to understand the meaning and scope of the activities. Therefore, the objective of this paper was to evaluate the ability of an Artificial Intelligence (AI) implementation to comprehend activities in a construction schedule. Following a mixed method in this research, the AI was implemented using the Bidirectional Encoder Representation Transformers (BERT) Natural Language Inference (NLI) with the list of the Construction Specifications Institute (CSI) Master Format (MF) 50 divisions activity codes. The result was that the AI has 0.56 accuracy, 0.50 precision, 0.85 recall and, 0.64 F1 Score.

5. FUTURE WORK

Despite the AI not being 100% accurate, this paper opens a wide variety of future research opportunities grounded on the mixed method used in this research with the four stages (Data Collection, AI Training and Preparation, Activity Interpretation, and Analysis). Some of those future research opportunities include: 1- Used other method to evaluate the NLP such as the Area Under the Curve (AUC) of the Receiver Operating Characteristic (ROC) curve, 2- Evaluating other NLP Encoder, 3- Comparing Performance among multiple NLP Encoders, 4- Implement a mixture of unsupervised and supervise NLP, and 5- Expand the number and type of schedule activities to be implemented just to mention a few. Upon achieving a higher level of comprehension future research could be directed towards using AI to assist humans in the preparation of construction schedules or perhaps prepare drafts of the construction schedules for the human to review.

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MULTI-ROBOT FEDERATED EDGE LEARNING FRAMEWORK FOR EFFICIENT COORDINATION AND INFORMATION MANAGEMENT IN SMART CONSTRUCTION

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ABSTRACT: *Smart construction involves a growing array of devices that generate extensive data, capable of enhancing construction efficiency and productivity. Nonetheless, the handling of this diverse and abundant information, along with the geographical spread of construction sites, poses challenges to effective communication and information processing within the management system. Multi-robot systems, as a new type of Internet of Things device, have the potential ability to coordinate workers to complete their work while serving as an edge node for information storage and processing. This paper presents a multi-robot federated edge learning framework that facilitates construction information management and communication. The work demonstrates the role of distributed databases in processing information during project execution, in contrast to centralized information systems. To address the intricacies of construction sites and the wide array of equipment involved, unmanned aerial vehicles and quadruped robots are employed as edge nodes. The formation of a federated edge learning framework ensures the real-time processing of massive data and data privacy issues. The Federated Multi-Robot (FedMR) framework is a global sharing model focused on preserving differential privacy protection. This framework is distributed to multiple edge robots in each round, enabling local real-time processing of robot tasks. The system can accomplish target detection and tracking of workers based on computer vision. Additionally, we collect MiC energy consumption data during the construction process and predict carbon emissions. Based on the implementation and testing of the system, it has been shown to provide structured and reliable information, fast local transmission, and the ability to process information in real-time. The system's ability to coordinate workers and process information makes it a valuable tool in smart construction.*

KEYWORDS: *Construction management, federated learning, multi-robots, Information management, differential privacy, Modular Integrated Construction(MiC).*

1. INTRODUCTION

The increasing development of the construction industry towards being smart and the concern about management informatics stimulate a higher requirement for adopting construction technology. Internet of Things (IoT), blockchain smart contracts, and AI in construction are emerging as the next wave in smart construction, with examples such as detecting the presence of objects in the construction environment to improve safety (Fang et al., 2018). The management of complex projects will be efficient, automated, and intelligent with computer vision technology (Xu et al., 2021). Prefabrication involves the use of different components from different manufacturers. This makes it difficult to standardize data sharing across the industry, leading to a lack of consistency in the data that is shared. And Prefabricated buildings, spearheaded by modular integrated construction (MiC) as a future trend in the construction industry, can lead to poor data sharing and communication resulting in the uniqueness of their supply chain (Wuni et al., 2022). The construction process is different from traditional construction methods. Prefabricated buildings are constructed off-site in a factory-controlled environment, where the materials and labor are streamlined and optimized for efficiency. This requires a unique supply chain that is focused on the procurement and delivery of materials to the factory, as well as the transportation and installation of the finished product to the construction site. Construction usually requires the cooperation of many stakeholders, which can be divided into four categories according to their functions: client, manufacturer, logistics company, and contractor. The process of modular construction involves various aspects of design, engineering, manufacturing, logistics, installation, and project management. Each stakeholder brings a unique set of skills and expertise to the project, including architects, engineers, contractors, manufacturers, transportation specialists, and project managers. And these multidisciplinary stakeholders have different expectations, interests, and motivations, and the plethora of participants in a construction project leads to low information transparency, inefficient transactions, and even frauds. (Luo et al., 2019) Today's construction is operating in highly dynamic environments, which requires the information facilities to be able to provide stable network services and adequate computing sources in interaction with the environment on site. For example, verifying the statuses of the modules can monitor the construction progress . At the same time, the high level of privacy and the large amount of information generated during the

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Xinqi Liu, Jihua Wang, Ruopan Huang, Wei Pan, *Multi-Robot Federated Edge Learning Framework for Efficient Coordination and Information Management in Smart Construction,* pp. 553-563, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.54

project management process leads to a decrease in efficiency. In order to effectively tackle the challenges posed by inadequate infrastructure and privacy concerns during the construction process, it is imperative to implement a robust on-site system architecture that facilitates mobile crowdsensing, shared storage, and processing of information from computational sources while ensuring data privacy. This technology is critical for the advancement of Construction 4.0, and can only be accomplished with ample computing resources and a reliable network. By bringing information technology to this traditional yet modern field, we can revolutionize the construction industry. The system can improve information transparency, reduce information asymmetry and facilitate collaborative work throughout the construction project lifecycle. Managers can keep track of the project's construction progress in real-time, identify problems and solve them in time to avoid causing construction problems such as deliveries delay, the absence of workers, machinery breakdowns, etc. Effective information sharing can also coordinate tasks between managers and workers, improve communication efficiency and optimize the construction process (Jiang et al., 2021).

The limitations of information technology, such as data transmission, make communication and data visualization in construction less efficient (Niu et al., 2015). This has a significant impact on the design of low-energy buildings, which require real-time monitoring of the environment and control. Niu et al. proposed A virtual reality integrated design approach to improving occupancy information integrity for closing the building energy performance gap (Niu et al., 2016). But this approach also generates a lot of private data due to the fact that the attitude of companies such as manufacturers towards new technologies depends on the environmental and organizational context (Pan & Pan, 2019). Building organizations can have concerns about the use of technologies that contain similar issues. In turn, this data cannot be fully utilized in a shared manner. A framework that can break through the efficiency of data transfer and address data privacy is necessary for the construction process.

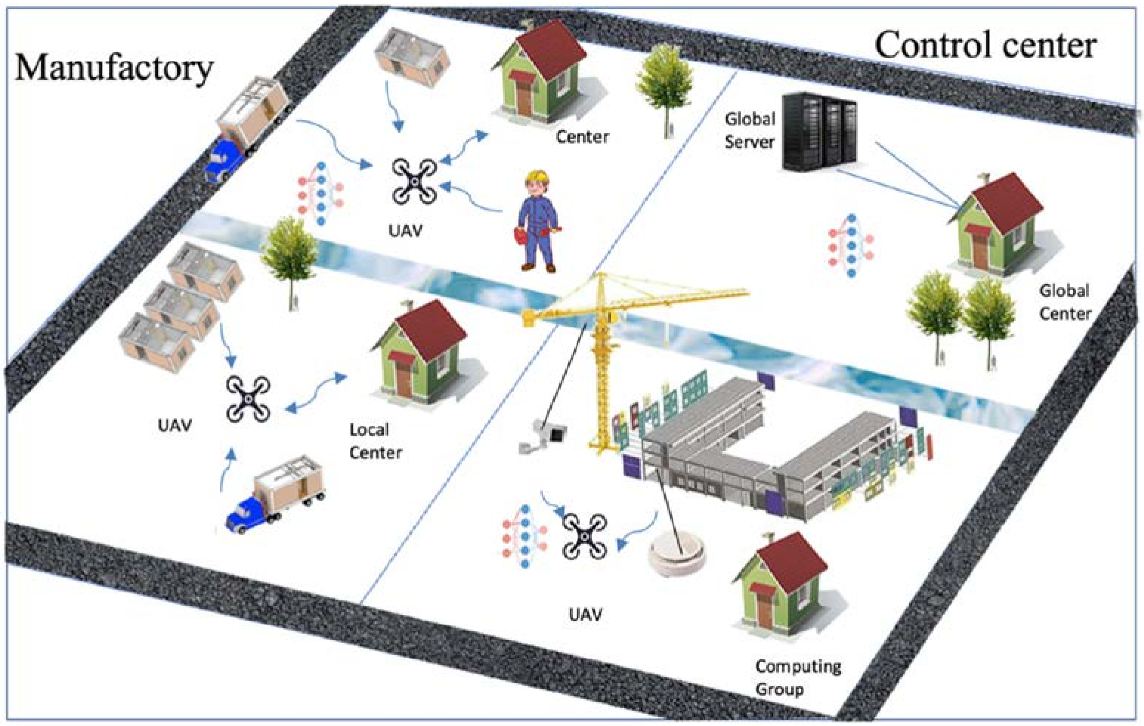

Fig. 1. An example of construction information management by federated learning

Fig. 1 Illustrates the multi-robot horizontal federated edge learning framework for construction information Management. The framework enables robots to gather information from workers and vehicles and transmit it in real-time through sensors to the robots. The robots then sample the information and process their query on the device. For instance, if one frame includes a vehicle, the robot will detect and send back the data to the user while another section of the sampled frame will be forwarded to the edge server for object detection, specifically the detection of the vehicle. Throughout the video analysis query processing lifecycle, the edge device and edge server collaborate to provide the user with detection results. By utilizing this framework, the system can effectively manage construction information by collecting and analyzing data from various sources, ultimately improving project efficiency, and reducing errors.

The increasing development of smart construction and the concern about the application of the IoT in construction stimulate a higher requirement for information exchange and communication quality. There are privacy issues in the transmission, storage, and analysis of data. These data relate to confidential industry information, such as the operations and costs of the companies involved. Institutional restrictions hinder information sharing between clients and contractors. Strict regulations undermine the efficiency of information sharing between clients and contractors. As factories, shipping companies, and contractors are independent. They cannot share data between them, which makes it difficult for project management as a third-party company to organize and coordinate the entire construction process. Site coordination requires the exchange of information between different contractors and sharing raw data between different contractors may compromise privacy and lead to problems such as communication barriers. The lack of information sharing between construction companies and suppliers is a significant barrier (Ojo et al., 2014) . Smart Construction is a method of construction that requires coordination in construction duration. A highly coordinated construction program of plant, transport, and construction is required. However, if clients and contractors do not accept relational matters as a long-term strategy, they will refuse to share implicit information (Yan, 2014).

Insufficient computing power equipment on site due to the complex environment of the construction site and the lack of well-established power and communication system. The raw data collected on the edge devices need to be uploaded to a cloud server for processing, which requires a lot of data transfer and processing time. For the construction of security systems, functions such as path planning and target recognition require real-time computing capabilities. While the majority of devices currently possess at least one image sensor and the ability to record and play high-resolution videos, they are deficient in the processing power required to execute intricate real-time computer vision algorithms. They are still unable to perform high-intensity performance computer vision tasks in real-time, with high frame rates and low latency (Honegger et al., 2014).

Star topology is widely used when the intelligence of the network is concentrated on the central node. However, the star topology has many disadvantages (Bisht & Singh, 2015). The star topology has many redundant links to ensure high connectivity, which results in high installation and maintenance costs and poor resource-sharing capabilities. Also, the communication lines are only used by the central and edge nodes on the line, which lead to communication lines being poorly utilized. Nevertheless, the central node demands frequent attention, and if it malfunctions, the entire network will come to a standstill. As computing evolves from centralized mainframe systems to many powerful microcomputers and workstations, the use of the traditional star topology will be reduced.

The purpose of this study is to introduce a multi-robot federated edge learning framework that can facilitate communication and information management in smart construction. The paper highlights the challenges posed by the large amount and wide variation of information involved in construction and the spatial dispersion of construction sites to the information management system (Akinosho et al., 2020). The paper propose the use of unmanned aerial vehicles and quadruped robots as edge nodes to process information during project execution. The framework is a worldwide sharing model founded on the principles of differential privacy protection. It gets distributed to numerous edge robots during each round, enabling local real-time processing of robot tasks. The system can accomplish target detection and tracking of workers based on computer vision, and predict carbon emissions. The authors demonstrate that the system can provide structured and reliable information, fast local transmission, and the ability to process information in real-time, making it a valuable tool in smart construction.

This section below sets the scene by giving an overview of the existing initiatives and status concerning construction information systems. The rest of the paper is structured as follows: Section 2 reviews the literature of federated learning, federated learning in construction, and distributed ledger technology. Section 3 discusses the research methodology and object selection. Section 4 presents the system architectures and federated edge learning. Section 5 discusses the applications to the construction industry and performance evaluation of the federated edge learning framework. Finally, Section 6 draws the conclusions and suggests future research.

2. LITERATURE REVIEW

2.1 Federated learning

Federated learning (FL) is a distributed machine learning scheme based on parallel computing that can overcome the challenges of data sensibility and data silos through the collaborative and decentralized neural network structure. FL has a high correlation with distributed learning, while it focuses on providing a collaborative model without privacy leakage (Li et al., 2020) At present, the FL has two mainstream open-source frameworks. Google

(Google, 2019) proposed a TensorFlow Federated (TFF) framework for meeting the demands of deep learning services in decentralized data. Webank (“Webank (2019a),” n.d.) presents the first industrial-level framework, Federated AI Technology Enabler (FATE) serves for cross-organizational architecture. Furthermore, Ramaswamy et al. (Ramaswamy et al., 2019) proposed the prediction of emoji in mobile keyboards, which is a successful application for model improvement and Secure Aggregation for the concern of stakeholder privacy. And Yang et al. (Yang et al., 2019) divide FL frameworks into three categories: vertical FL, horizontal FL, and federated transfer learning. In the case of vertical Fl, data is partitioned in the vertical direction by the feature dimension. Horizontal FL is suitable for cases in which data are multiple in sample space and a set number of overlaps among the feature of data storage in various nodes. Upon most occasions, data shares are quite distinct from sample space and feature space. Therefore, federated transfer learning can solve the problem in this setting is poor data quality without data labels (Li et al., 2020).

2.2 Construction information management

Having access to data at the right time for construction managers can assist project construction in assessing the construction performance of the corporation and subcontractors (Carrillo et al., 2013). When implementing construction information management, accurate data recording and comprehensive data analysis help to establish the credibility of stakeholders (Yang et al., 2019). Construction is a complex, one-off manufacturing process that involves many businesses, including design, manufacture, and transport. To assess the risks linked to each stakeholder, unprocessed data is necessary. Forecasting stems from data mining, a result of the methodical management of construction data. In addition, based on the data simulations, the manager can predict the potential problem area and plan for them (Arayici et al., 2012). With the completion of the first phase, the requirement for additional equipment and material in the second phase is identified. The analysis also provides construction stakeholders with visual information on project progress (Doloi, 2013). With the better access to and updating of the management system, the raw data should not be recorded with simple storage. It also provides data analysis servers. The potential for innovative algorithms based on artificial intelligence to support efficient construction processes (Pan et al., 2022). Data analytics and IoT are useful for the analysis of construction impact on parameters. In construction, construction information management is as important as construction, as information affects all construction-related activities (Kim et al., 2013).

3. METHODOLOGY

3.1 Problem definition

The primary focus of this present research is on information processing, analysis, and collation in construction scenarios. To achieve the study aim, construction robots have been designed as computational nodes, each corresponding to a construction safety monitoring device. These monitoring devices include cameras such as RGB, RGB-D, and LIDAR. Construction robots can be integrated as computational nodes, and can assist in the construction process while also collecting data and training models locally. This local processing ensures that data safety functions can be achieved while analyzing data on-site. In the context of construction safety monitoring, construction robots equipped with safety monitoring devices can help ensure safety compliance in construction sites. Additionally, they can help identify potential safety hazards, such as structural instability or unsafe working conditions. Furthermore, the collected data can be processed and analyzed locally, without the need to transfer sensitive information to external servers, ensuring data safety and privacy. By doing so, data can be analyzed in real-time, enabling quick decisions and actions to be taken to prevent accidents or hazards.

By utilizing the FedMR approach, data sharing is minimized, and data privacy is protected while effectively predicting the facial fatigue status of workers in real-time. This approach can aid in improving construction safety by enabling prompt interventions, when necessary, ultimately reducing accidents and improving the overall safety of workers and equipment vehicles in the construction scene.

3.2 Construction information framework overview

Construction is a complex process that generates a vast amount of information, as depicted in Fig. 2. The construction information is created from the design phase at the start of the project, and all project-related data is stored in a distributed manner on the construction site. This includes the management of approvals and material information, installation and transportation processes, and the information can be collaboratively managed. Through federated learning, all resources can be integrated securely, and machine learning can be used to efficiently integrate resources and make plans. Construction projects are complex endeavors that involve a multitude of stakeholders, including architects, engineers, contractors, and subcontractors.

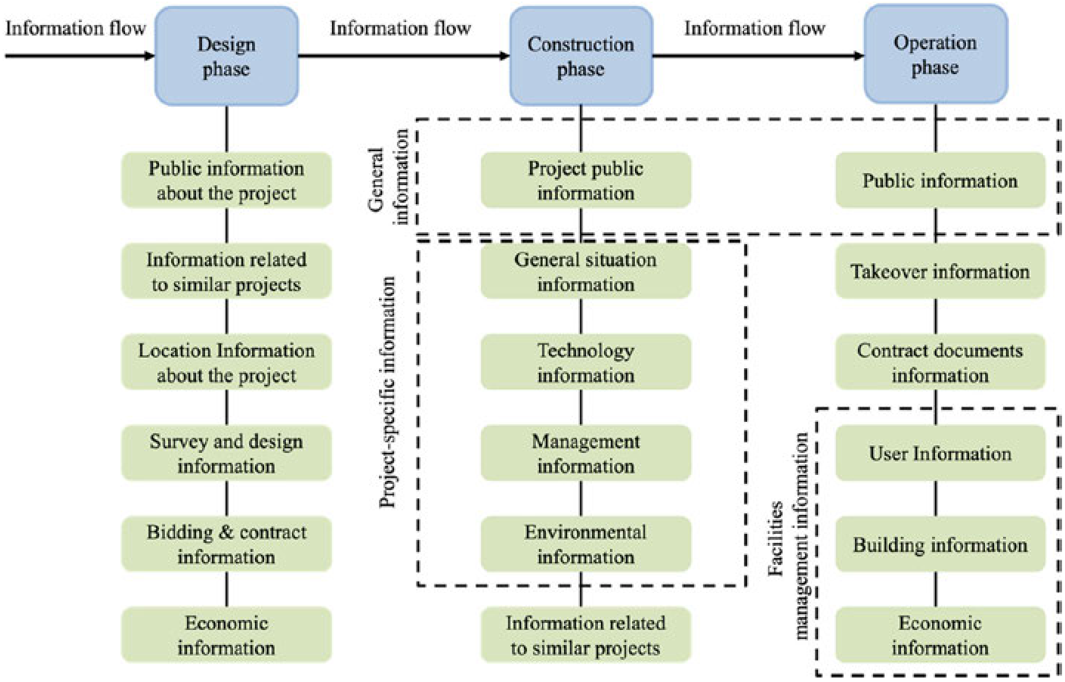

Fig. 2. Construction information on the different phase

Coordinating the information flow among these entities can be challenging, especially given the extensive data that requires sharing and processing. Federated learning presents a promising remedy, providing a secure and efficient approach for construction information management. It enhances efficiency and accuracy without compromising data privacy and security, as multiple parties collaboratively train a model without sharing raw data. When well-implemented, federated learning aids stakeholders in early problem identification and informed decision-making, ensuring project success.

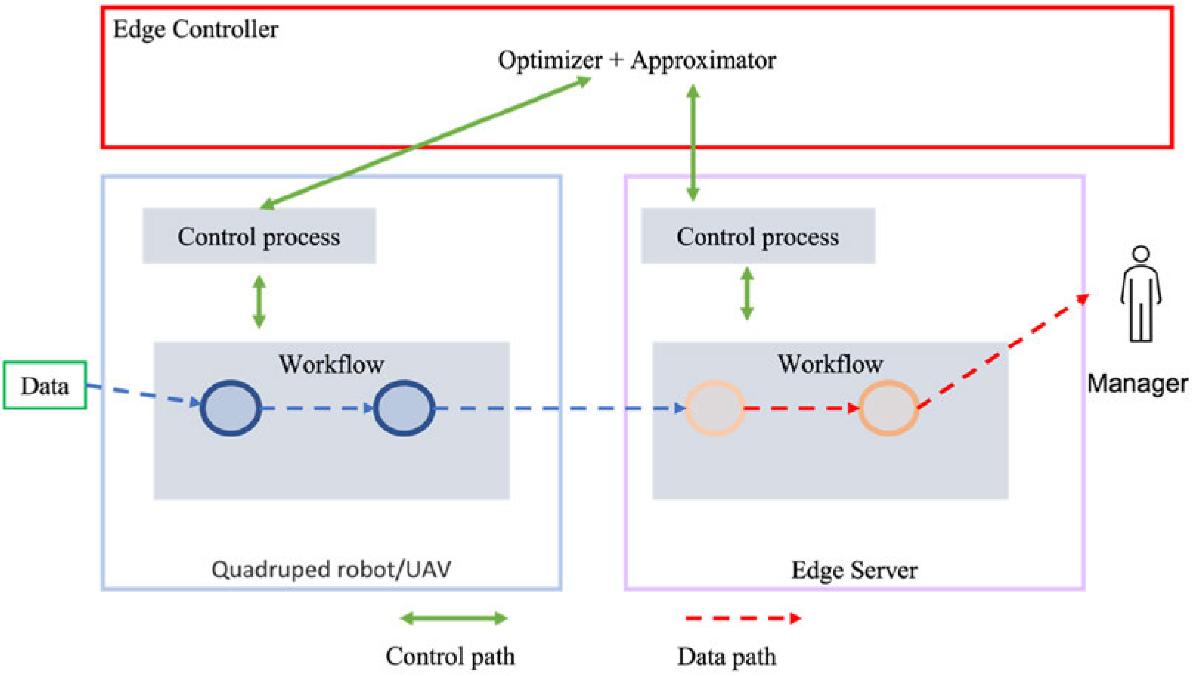

Fig. 3. FedMR system framework overview

The Federated Multi-Robot (FedMR) framework consists of an edge controller, a series of multi-robot systems, and servers, as illustrated in Fig. 3. The data flow involves two routes: the data path and the control path. A user's query traverses through the robots and servers in the workflow, which consists of a series of functions. In the data path, construction takes place sequentially from the first function to the last one in the workflow. Following data processing through this workflow, the resulting outputs are then delivered back to the user.

By employing the FedMR framework, construction information can be managed efficiently and securely, enabling prompt interventions when necessary and improving the overall safety of workers and equipment vehicles on the construction site.

4. APPLICABILITY OF THE FEDMR SYSTEM

To validate the viability of the approach, experiments were conducted to detect targets in images using a quadruped robot that captured local video data. The system carried out target recognition at the robot's side when the edge server retrieved images of vehicles. The training dataset for detecting moving objects in construction sites (MOCS) was preloaded into the robot.

In essence, the system's target detection capabilities were put to the test using real-world scenarios. By setting up video data collected by the quadruped robot, the system was able to accurately identify and classify targets within the images. The edge server, which received images of vehicles, promptly recognized the target objects, thanks to the training dataset preloaded in the robot. The MOCS dataset proved invaluable in training the system to detect moving objects in construction sites. By integrating the dataset into the robot, the system was able to recognize and classify objects in real-time, even in complex construction environments. This approach demonstrates the effectiveness of preloading training datasets into robots, enabling them to perform target recognition efficiently and accurately.

4.1 Environment setting for image test

The experiment, depicted in Fig. 4, employs YOLOv8 on Pytorch 1.8.1. The NVIDIA RTX3090 GPU serves as the platform for training and testing the model. Due to the rough road surfaces present in the construction site, a quadrupedal robot was selected as the ideal load-carrying system, as a typical wheeled chassis would have struggled to navigate the build environment with ease.The industrial camera used in the experiment is DF100-1080P (JIERUIWEITONG), while Unitree Go1 and DJI M200 function as edge devices. During the training phase, the new model incorporates parts of the pre-trained model from YOLOv8x. Since YOLOv8 and YOLOv8x share most of the backbone (block 0*8) and some of the head, it is possible to transfer a wide range of weights from YOLOv8x. Leveraging these weights during training can save significant time and computational resources. Overall, the use of YOLOv8 on Pytorch 1.8.1, combined with the powerful NVIDIA RTX3090 GPU, enables the model to train and test efficiently. Additionally, the use of industrial cameras, as well as the Unitree Go1 and DJI M200 edge devices, further enhances the experiment's reliability and accuracy. By incorporating pre-trained models and weights, the experiment provides a practical approach to target detection that can be easily adapted to a wide range of scenarios.

Fig. 4. Quadruped robot-based edge devices

4.2 Object detection in federated edge learning

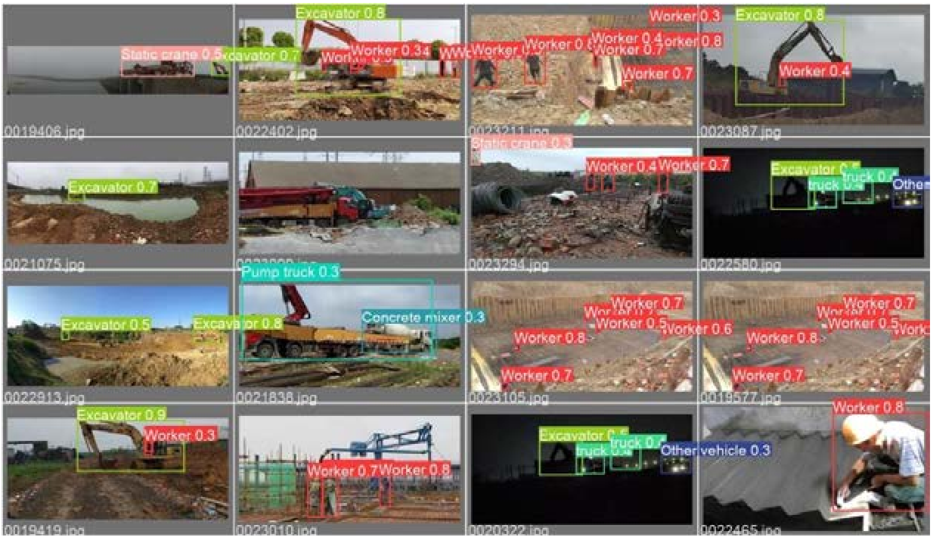

Fig. 5. Results of a target recognition system based on the FedMR framework

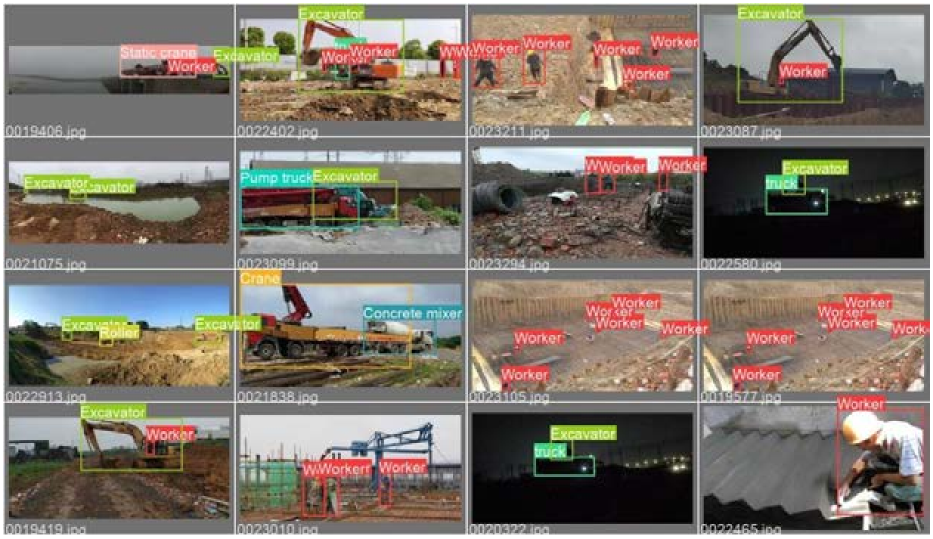

Fig. 6. Validated datasets with labels.

As illustrated in Fig. 5 and Fig. 6, the model trained on the local data training set achieved impressive results in target recognition. All targets were recognized compared to the labelled images. However, some of the worker targets had smaller IoU values when they were smaller in size. On the other hand, large vehicles were well recognized if they were presented as a whole. The best results were obtained for excavators.

When the edge server makes a query for a relevant target, the query image can be transferred back to the corresponding server. This enables the data to be trained and queried under local conditions, facilitating the management of information for construction while maintaining data security. By utilizing this method, administrators can access the information they need for security, management, etc., without having to access data from other departments.

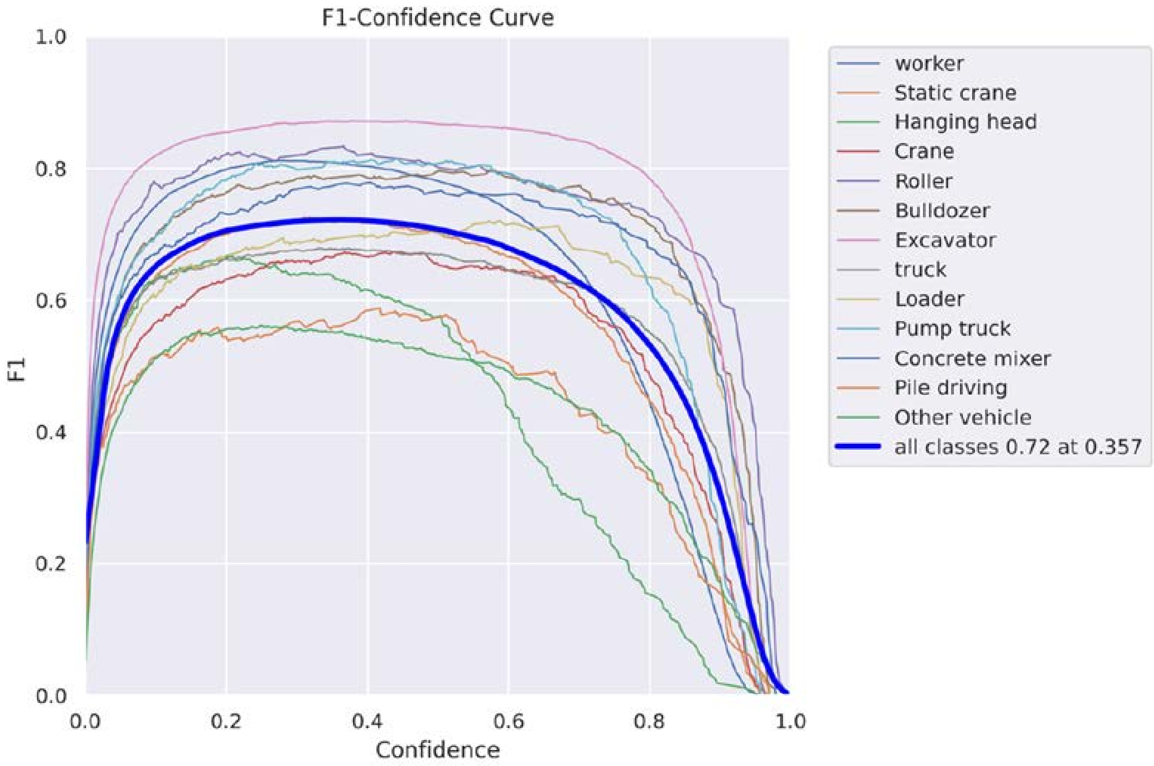

Fig. 7. The result of F1-scores

As shown in Fig. 7, the F1(H-mean) score is a combined evaluation indicator of recall and accuracy. The F1 value represents the division of the arithmetic mean by the geometric mean, with a higher value indicating better performance. Analyzing the Precision and Recall formulas in the context of this reveals that when the F1 value is low, there's a relative increase in True Positives and a decrease in False Positives, leading to a relative increase in both Precision and Recall. Essentially, F1 is a weighted measure that considers both Precision and Recall.

$$F1 = \frac{2}{\frac{1}{P} + \frac{1}{R}} = \frac{2 * P * R}{P + R}$$

The P is the precision of the YOLOv8 based on FedMR , and R is the recall of algorithm.

The worker and crane identification had the best F1 score. The confidence of all categories was 0.72 at F1=0.357, which is a significant improvement compared to the YOLOv8 standard of 0.65. This indicates that confidence is also guaranteed to be very good at higher recall. This data proves that edge nodes can provide good data processing capabilities, and the local model can process the data collected in the field in real-time. With a confidence level of 0.35 at 0.70 in comparison to YOLOv8 utilizing a non-FedMR framework, it is evident that the FedMR framework significantly enhances information processing capabilities. This improvement leads to better performance, even when data processing is restricted to a localized environment.

The FedMR have adapted the original FederatedAveraging (FedAvg) algorithm to our framework as shown in **Algorithm 1**. This aim is to investigate the impact of various data divisions and federated learning settings. To achieve this, the framework have modified the FedAvg algorithm to a FedMR algorithm by replacing the server-client communication framework, such as SocketIO, with a method that saves and restores checkpoints on hard-devices. This simplifies the model aggregation process. However, our implementation can also be effortlessly transferred to FedAvg.

Algorithm 1 FedMR

Input: N client parties$\{C_k\}_{k=1..N}$,total rounds T , and Server side S;

Output: Aggregated Model ω

S initializes federated model parameters, and saves as checkpoint. Client parties $\{C_k\}_{k=1..N}$, load the checkpoints.

for $t = 1, ..., T$ do

for k= $1, ..., T$ do

$\omega_k = \omega^{(t)}$

each client $\{C_k\}$ do local training:

for $i = 0, 1, ..., M_k$ do

(M_k is the number of data batches b in the client C_k)

client $\{C_k\}$ computes gradients $\nabla\ell(\omega_k, b_i)$

update with $\omega_k = \omega_k - \eta\nabla\ell(\omega_k, b_i)$

end for

save ω_k results to checkpoints.

end for

S loads checkpoints and get averaged model with $\omega^{(t)} = \frac{1}{N}\sum_{k=1}^{N}\omega_k$

end for

Return $\omega^{(T)}$

5. CONCLUSIONS

FedMR has demonstrated its versatility as a comprehensive model for handling information, optimizing processes, and monitoring isolated data. This empowers robots to offer insights, predictions, and warnings tailored for individual distributed construction workers prior to task execution at the work package level. However, existing machine learning approaches for modeling, optimization, and monitoring in construction information management necessitate data sharing or aggregation from each company, posing privacy risks and failing to deliver personalized monitoring of construction site conditions.

Therefore, this paper has proposed a horizontal federal learning framework, FedMR, to aggregate cryptographic information data parameters from different building stakeholders without compromising privacy and personalize the model differently based on the jobs each robot is responsible for. The model is improved based on the Fedvision model, utilizing the multi-robot as the edge device. The testing process is experimentally validated through the retrieval of image information by managers, using a target detection approach by training and testing locally. After experimental verification, the efficiency of YOLO algorithm can be improved in FedMR framework can be improved by 1.5% under the premise of user privacy F1 can be improved. The evaluation results show that the proposed FedMR can achieve mainstream YOLO recognition performance, and privacy is well protected. However, there is still room for improvement in terms of model performance and scalability. Future research should focus on exploring the potential of incorporating more advanced machine learning techniques such as the Large language model. Additionally, as the use of robots in construction becomes more prevalent, it is important to continue to prioritize the development of secure and personalized monitoring solutions to ensure the safety and efficiency of construction processes.

6. ACKNOWLEDGE

The work described in this paper was supported by the Research Impact Fund of the Hong Kong Research Grants Council (Project No.: HKU R7027-18) and the 43rd Round University Research Committee PDF/RAP Scheme of The University of Hong Kong.

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ROBOTIC ASSEMBLY AND REUSE OF MODULAR ELEMENTS IN THE SUPPLY CHAIN OF A LEARNING FACTORY FOR CONSTRUCTION AND IN THE CONTEXT OF CIRCULAR ECONOMY

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ABSTRACT: *Although robotic solutions have been making significant contributions to fabrication environments, implementations in the construction are rare. It seems a disconnect between the industries exists where in construction the high number of non-uniform work tasks, the wide assortment of types and shapes of building materials and elements, and the presence of human workers creating safety hazards make the deployment of rather rigid robotic manipulators on construction sites much more complex than in production-like work environments. To advance construction with robotic solutions, it could prove beneficial to make each sector aware of the barriers that exist, and likewise, introduce a physical space for joint experimentation with state-of-the-art technologies from both fields. One way of alleviating this issue is to connect the sectors by providing hands-on education and research experiences, defined hereby as Learning Factory for Construction (LFC). This paper presents a scaled-down version of a LFC that has a robotic manipulator perform fully-automated and precise assembly, deconstruction, and reuse tasks of modular construction elements, whereas the elements are tracked with fiducial markers according to a known building information model and schedule. Furthermore, the FLC continuously gathers and analyzes data for performance, measures successful completions, assembly times, and potential quality defects. This project involved Masters level students with domain expertise from architectural, civil, and mechanical engineering in a cross-disciplinary and collaborative learning exercise of building a working prototype within a semester-long study project. Beyond the core tasks of the digital design and robotic application, the group developed theoretical concepts and limitations for more holistic views on circular economy, lean production, on- and off-site logistics, modularization, and construction safety, just as expected from a LFC. It is anticipated that the next generation of professionals working in the built environment and intending to solve some of the larger and more complex societal problems will require both the technical and communication skills that a LFC can stimulate. Therefore, LFC is expected to become an important component of active learning environments.*

KEYWORDS: *Active learning environment, automation and robotics, building information modeling, circular economy, human-machine interaction, learning factory for construction, modular construction, next-generation tech-savvy engineers, rapid prototyping and testing, renovation, reuse of materials.*

1. INTRODUCTION

For the past decades there has been an increased interest in robotic technology in construction applications. Economic projections foresee a prospering field and actual widespread usage in practice, requiring new policies and rules across the impacted industries (EC, 2022). However, many challenges still present themselves regarding robots in construction. Simple tasks that prove easy to execute for humans, prove extremely difficult for robotic manipulators due to a lack of perception and cognitive abilities. The size and weight of robots in industrial work environments, often tackling singular and highly repetitive tasks, does not fit the challenging, complex, and highly dynamic work environment that exists in construction sites. Yet, finding the necessary functionality and usability are a few of the additional barriers that exist and prevent robots from mainstream implementation. Despite some recent and rather serious interest from the industry, robotic applications in construction have stayed limited to niche research or exploration projects. Automated and robotic brick laying machines (Usmanov et al., 2017; Ravi et al. 2021) and additive manufacturing are some examples (Teizer et al., 2016).

To enable the use of robotics, suitable methods to assist the robots are necessary to consider. Yet, they are difficult to develop as construction touches a multi-disciplinary field that makes it challenging to find acceptable solutions. A few somewhat isolated disciplines (and stakeholders) are: design (architects/planners), construction (civil engineers), machinery (mechanical engineers), and systems and processes (industrial engineers). While innovation in any field, like in construction, calls for lifting the boundaries between these domains, a further major aspect to consider before introducing robotic applications in construction is to maintain a high level of trust, productivity, and safety in new technologies (EC, 2022).

Change to fabrication environments came over decades, with fully-automated solutions replacing isolated and

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Jochen Teizer, Kepeng Hong, Asger D. Larsen, Marcus B. Nilsen, *Robotic Assembly and Reuse of Modular Elements in the Supply Chain of a Learning Factory for Construction and in the Context of Circular Economy,* pp. 564-573, DOI 10.36253/979-12-215-0289-3.55

highly repetitive work tasks humans would not endure. The typical construction work environments yet may demand a similar time frame and even more. For example, active human-robot collaborations are supposed to solve the sector's rather complex and interconnected work tasks. The involvement of multi-trades' expertise and the manifold types of product or material specifications constitute a few of the other but plentiful technical challenges that semi- or fully-automated robotic solutions are envisioned to solve before decision-makers would buy into them for final field use (Slaughter, E.S., 1998; Goodrum & Haas, 2016)

Yet, the effects that a transition to robotic labor would have on construction can include improvements to construction industry-wide problems, including but not limited to achieving higher productivity and better safety and health performances. As such, prioritization of human time and purpose of life and health, and ease of system installation and maintenance, to name only two criteria, reflect the current construction industry's efforts towards digitalization, automation and robotization (Yamamoto, 2020).

The concept of a Learning Factory (LF) is not new, and yet they hardly exist for construction purposes. Teizer and Chronopoulos (2022) expressed that a Learning Factory for Construction (LFC) can provide a useful active collaborative working environment for engineers that are interested in exploring prototypical solutions that have the potential to solve known industry problems. In their articulated vision, a LFC provides the explorative collaboration space to (a) detect the organizational barriers that prevent innovation, (b) allow objective and scope definitions by understanding the technical limitations in existing work processes, and (c) create prototypical hard- and software solutions that can be tested on small but at realistic scale and with little risk of losing large investments. Gaining knowledge in a LFC first is required to later adapt solutions to a larger workspace and with increased autonomy. And yet, students that participate in a LFC should have fun, like Teizer et al. (2020) and Wolf et al. (2022) found out when observing construction apprentices that played serious games for construction safety.

As the widespread application of robotics in manufacturing industries has significantly improved productivity and efficiency, there has been significant research interest in construction robotics. Besides reducing project delivery delay, construction robotics can benefit the workers by assisting them with non-ergonomic tasks (e.g., lifting weights) and taking over dangerous activities (e.g., demolition). However, the implementation of construction robotics heavily relies on manual input from task to task due to the complicated nature of construction activities. For instance, the difference between as-built and as-designed models during the construction stage can be challenging for preprogrammed construction robots to understand the changing environment at the construction site. Only in combination with a higher level of digitalization construction robotics can it be effectively implemented for automated or semi-automated construction. Emergent methods and technologies, such as BIM and vision-based object recognition, collaborate with construction robotics to complete the workflow of automated construction. Such collaboration requires various fields of engineering to understand all involved technology and the interplays between these technologies. Figure 1 integrates many of the currently existing digital technologies and how they relate to each other. Highlighted in grey background color are those that are part of this LFC.

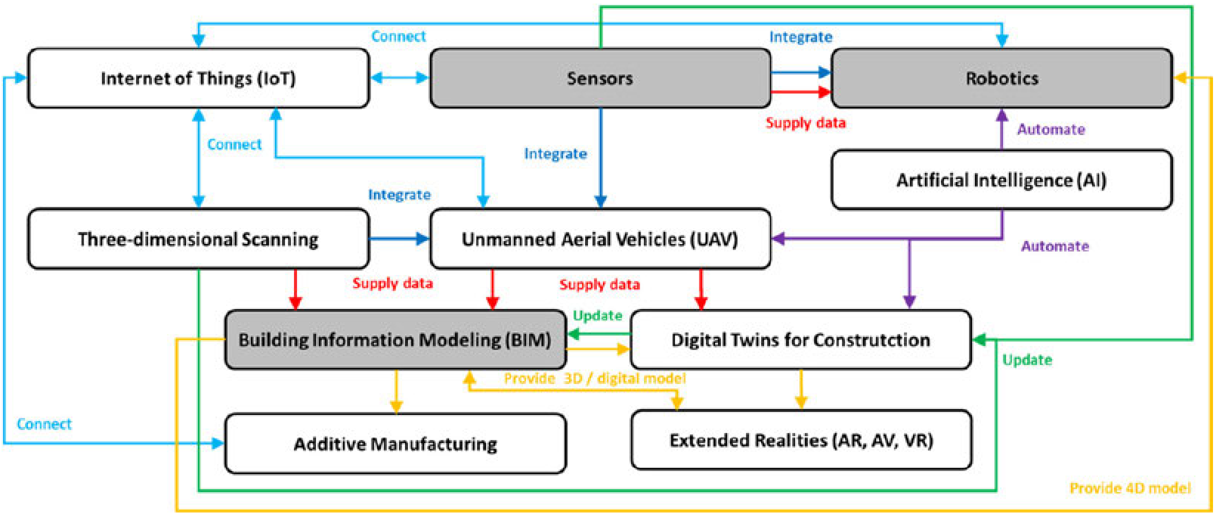

Fig. 1: Overview of relation between digital technologies; modified, originally from EC (2021),

The goal of this paper is to demonstrate the viability of the integration of a robotic manipulator into a LFC, displaying the advantages of using modular components in the context of autonomous construction in a circular economy. The following sections first review the background, then introduce the developed LFC, a scaled-down version of a building construction site, and finally demonstrate its capabilities in a case study where a robotic manipulator handles modular elements for building assembly and reuse under some of the typical real constraints that exist in the construction supply chain and in a circular economy.

2. BACKGROUND

Several existing cases have shown that assembly processes using robotic manipulators are favorable. Wang et al. (2020a) stated that robotic construction was both faster and more accurate compared to conventional manual methods by construction workers alone. However, it was stated that robotic solutions were limited to being either conducted in non-complex work environments or limited to handling specified objects. In other words, robotic solutions still required some aspects of human labor to complete complex activities. These limitations pose some of the biggest challenges to overcome.

The recently-completed research project HEPHAESTUS proved successful in installing curtain wall modules using a large-scale cable-driven robot alongside a robotic manipulator, but many improvements were left to be implemented (Iturralde et al., 2020).

Using robotic manipulators for construction has shown to be easier executed when introducing the modular and parametric design in assemblies of complex constructions. Research on modular design for robotic construction showed that it is possible, using modular components, to verify the design and construction process through simulations (Sun et al., 2022).

Using timber panels, which are identified by computer vision and machine-readable QR codes, has proved to make it possible for a robot arm to do insertions of panels to create simple assemblies (Rogeau et al., 2020). In addition, a robot arm using standardized timber was able to construct complicated structures with high precision. Results from Leng et al. (2020) showed the benefits and possibilities of utilizing standardized materials, with precise parameters being a key factor. A similar research with timber addressed the issues of wood being a natural and imprecise material which complicates handling, highlighting the issues of production tolerances (Hasan et al., 2019).

The notion of having robots build from a digital model has been investigated in several papers, with a focus on exporting Building Information Modeling (BIM) to a robot from an as-designed model or importing the physical as-built model for guidance purposes. Likewise, using a Digital Twin for Construction (Sacks et al., 2020), the process of having a robot build from a BIM and updating the as-built model using sensor data was validated (Wang et al., 2020b). At the moment, software packages are being developed to help link BIM-based design with robot control which could ease the process of future digital-to-physical model building (Yang et al., 2019). Slebicka et al. (2021) placed an important vision for Fabrication Information Modeling (FIM) that intends to close the gap between BIM and Digital Fabrication that, at some point in time, will heavily depend on automation and robotics.

While only a small amount of the above-mentioned research addresses the interaction between autonomous robots and human workers, human-robot interaction proves to be detrimental when considering on-site safety (Wu et al. 2020). With the prospect of robots in construction, it is recommended to also investigate their social impact since the potential changes to workplaces will require workers to acquire additional skills, competencies and responsibilities (Karl et al., 2018). A proposed method of tackling safety is to introduce the concept of an LF, which emphasizes hands-on experience. LFs offer a high potential to improve education, training, and research in a controlled environment (Abele et al., 2017).

Gharbia et al. (2019) concluded that rapid prototyping assisted in the creation of robotic solutions. In this context, introducing a robot manipulator into a LFC would educate on, and increase the awareness of the capabilities of autonomous robots in a construction work environment and help involved project stakeholders (engineers and workers) adapt increasingly advanced technologies to a construction site.

Related to this effort, robots of different sorts have already been introduced to various Learning Factories in relation to Industry 4.0. Several researchers have included robotic arms in their own specialized Learning Factories, albeit with a focus on manufacturing and assembly (Matt et al., 2014; Kaménzy et al., 2018; Nardello et al., 2017).

As with Industry 4.0, the recent technological advances will gradually replace the roles of humans in construction, in what is coined Construction 4.0 (Sawhney et al., 2020). However, the challenge of integrating a robot into a LFC environment with the purpose of improving construction processes is yet to be investigated.

3. ROBOTIC MANIPULATOR IN A LEARNING FACTORY FOR CONSTRUCTION

The first part of this section briefly explains the relevant backgrounds of the research methods employed in this work of Masters-level students in a semester-long study project that utilizes the LFC at the Technical University of Denmark. Next, the hard- and software components of the LFC are introduced. Experiments and results follow with a discussion summarizing the lessons learned at the end.

3.1 Introduction to components

3.1.1 Learning factory for construction

LF has proven to be an effective way to provide active hands-on learning (Abele et al., 2017). LF typically reproduces or simulates a production environment, allowing participants to gain practical knowledge and skills in a controlled setting. In addition, LF also provides a platform for researchers to investigate and improve processes and workflows. In this case, our LFC is meant for university students but can also involve apprentices or full-time professionals, like workers, technicians, and engineers from the construction industry. The purpose of our LFC is to provide the physical space that facilitates education and research on automation and robotics in construction.

3.1.2 Robotic manipulator

A robotic manipulator performs tasks as a human arm (Matt et al., 2014). In our case, the robot mimics a mobile or tower crane on a construction site. Our LFC consists of multiple modules that include robotic elements, of which only the robotic manipulator UR5e, its mounted camera and gripper, and a computer will be explained in the further text. Details of the other existing components of our LFC can be found in Teizer and Chronopoulos (2022). While these eventually will be connected to each other, this paper introduces the part of the LFC that simulates the process of three steps in automated modular construction: automated assembly, disassembly, and reuse according to a BIM-based building design. The UR5e is made of several interconnected segments, has joints, and one end-effector, allowing it to make rotary and linear movements. The end-effector performs assigned tasks at any position within the spatial coordinates of the robotic arm. The learning factory uses UR5e as the robotic arm and mounted gripper as the end-effector so that it can grab, lift and place any given components at the assigned positions. It has six degrees of freedom (x, y, z, roll, pitch, yaw), whose value can be changed so that the gripper mounted at the end of the arm can be moved to desired position and orientation. There exist three types of movements, *moveJ* (the robot moves each joint independently), *moveL* (the robot moves in a straight line), and *moveP* (the robot moves following the designed path).

3.1.3 Building information model and construction schedule

BIM is a comprehensive and collaborative method across the whole building life cycle (Oraee et al., 2017). Yet, it has less been used in combination with automation and robotics than other applications. Our LFC uses commercially-available BIM software for the manual design of a fictive modular building project and, likewise, is the sequence of constructing the modular elements planned digitally. While this may imply a detailed construction schedule comprised of the precise timing and dependencies of the construction tasks, only the Work Breakdown Structure (WBS) is needed. The BIM software is also used for visualization purposes. Otherwise, the IFC format contains geometry and position information for each of the modular elements and the task sequence.

3.1.4 Building materials

The building is constructed with standardized physical models using the UR5e. The pieces are made from lightweight plastic and come in several shapes.

3.1.5 Object detection

In order for the robot to handle the modular elements, object detection and recognition with final localization is required. Object detection is made possible by computer vision that identifies and localizes the modular elements of next interest within the video frame capture. There exist two main approaches for object detection, traditional (e.g., rule-based, handcrafted features) and deep learning-based approaches. Out LFC integrates traditional object detection algorithms for construction sites and modular component detection.

3.1.6 Human-robot interaction

Human-robot interaction happens only twice in this part of the LFC: first, to place new modular elements in the arrival area to the simulated construction site that is within range of the robot arm, and second, when the building owner makes a choice of selecting a building design and floorplan. Otherwise, the developed module of the LFC operates fully autonomously, as explained in the following.

3.2 Methods

The framework of the LFC is shown in Figure 2. It comprises two parts. The first part is a remote control, where students in the role of an architect or civil engineer upload their IFC file to the computer. Note that the modular building designs of the students allow some variation but still follow the material specifications and parameters that were given to them beforehand. The computer extracts the geometry and position information of each modular building component and determines the construction sequence. The spatial and temporal information of construction is translated into robot commands and then sent to the robot for controlled execution. The manipulator first scans the entire site to locate and map the coordinates of the material pick-up, the temporary depot, and the construction zones. When ready, the robot finally receives the building commands to start the construction process.

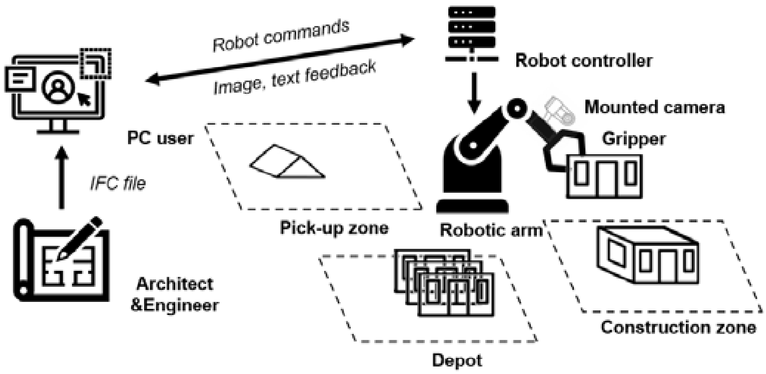

Fig. 2: Learning Factory for Construction (LFC) at the Technical University of Denmark: Construction site module.

The hardware and software requirements and descriptions for the learning factory are listed in Tables 1 and 2. The BIM translation and robotic remote control are implemented in a Python environment due to its simplicity and extensive library support.

Table 1: Hardware in the construction site module of DTU's LFC.

Equipment	Description
Robotic manipulator	UR5e for grabbing, lifting, and placing building components
Camera on end-effector	OnRobot RGBD camera for object detection and as-performed data collection
Computer	Processing BIM files, translating commands, receiving and processing data, control

Table 2: Libraries and software for the learning factory

Library and applications	Version	Description
URX	2.0.1	UR5e remote control and program execution
IfcOpenShell	1.6.1	IFC file translation and querying
OpenCV	20.10.22	Visual detection ad recognition
BlenderIFC		IFC file editing and viewing

For reliable object detection, the camera uses fiducial marks attached to the construction site and building components to recognize the different objects, as shown in Figure 3.

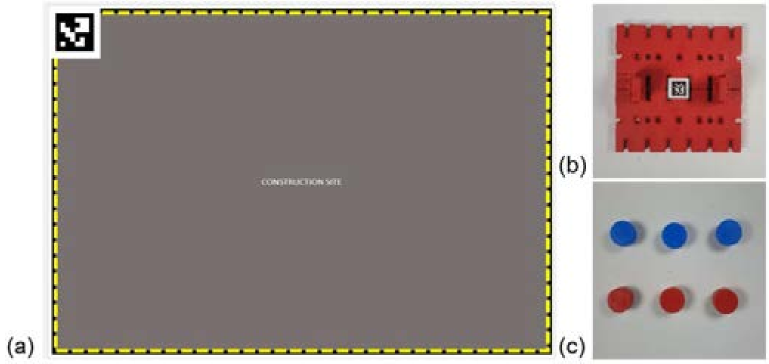

Fig. 3: Examples of (a) a zone and (a) modular building elements, all marked with different fiducial marks for object recognition. Note. The elements are further detected by shape and color.

3.3 Implementation and preliminary results

The preliminary implementation of this component of DTU's LFC is shown in Figure 4. The layout and setup follow the concept mentioned earlier. For a simplified demonstration, a basic two-story building consisting of 5 IFC elements is designed, shown in Figure 5. The five components are positioned at distinct heights so that the algorithm can easily sort the order of construction. Figure 6 shows the simplified modular building elements to which each unique fiducial markers are attached. Existing computational algorithms later detect and recognize the fiducial marker when it is within the field-of-view of the mounted camera on the end-effector.

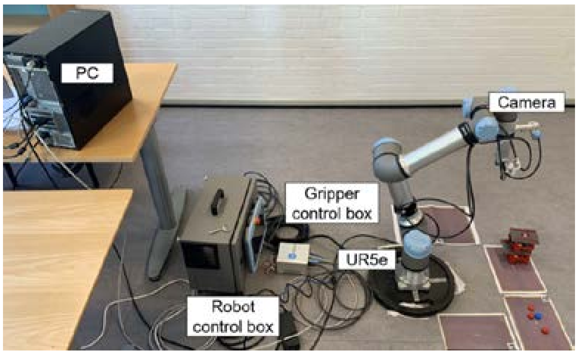

Fig. 4: Experimental setup of LFC.

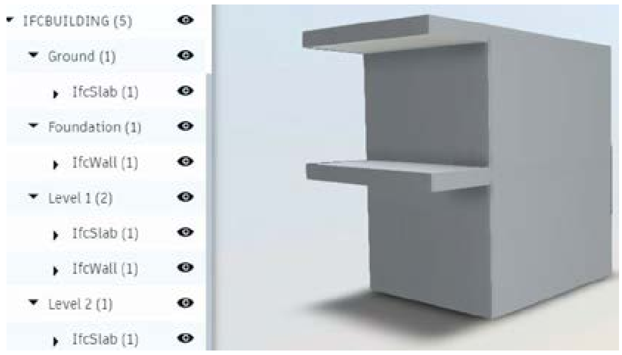

Fig. 5: IFC model of the 2-story modular building project

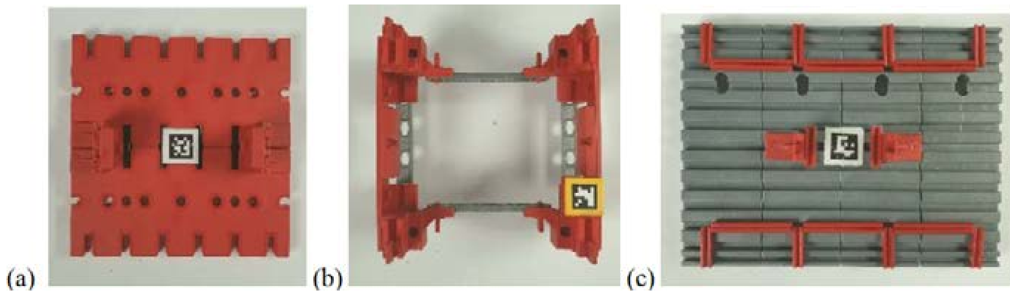

Fig. 6: Modular components: (a) foundation, (b) wall, and (c) floor.

Figure 7 illustrates the construction process. After the students load their IFC file, the computer extracts the spatial information of building components and determines the construction sequence. The corresponding list of the modular elements and the building sequence is shown in Table 3. The robot registers the coordinate of the construction sites by using the mounted camera to detect the fiducial markers of the zones. After the coordinate system is registered, the robots start to detect, grab, lift, and place the modular construction elements iteratively until the last component is assembled onto the building. Reversely, the disassembly process can also be achieved. All modular elements are taken apart and placed in a temporary storage zone (called depot). Next, human interference is needed if the next phase of the building lifecycle is of interest to the student. The student can choose to select an alternative building design, upload it, and the new building process can start again. Note, whenever possible, the robot reuses parts of the modular building elements lying in the depot. Once the second building is completed, typically, the LFC experience stops.

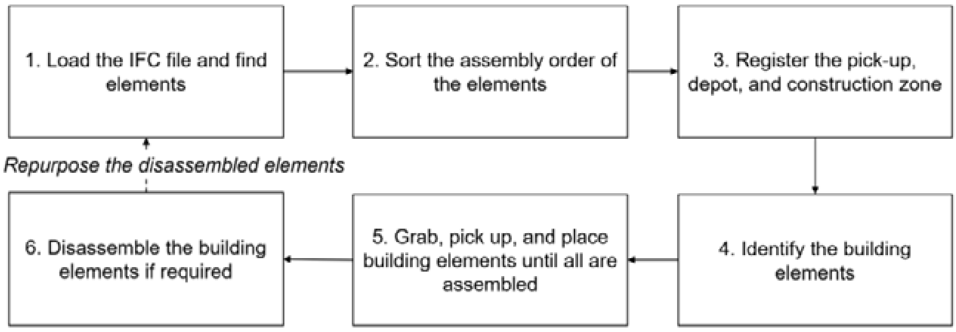

Fig. 7: LFC-workflow of the robotic manipulator module: First the design, then the robotic assembly and disassembly, optional: re-design and -use.

Table 3: List of the modular building elements and example of a building sequence by the ascending z coordinate

Number	Elements	Coordinates	Sequence
1	'Foundation:297060'	(x1,y1,z1)	1
2	'Floor:301328'	(x2,y2,z2)	3
3	'Floor:301575'	(x3,y3,z3)	5
4	'Wall:304810'	(x4,y4,z4)	2
5	'Wall:305546'	(x5,y5,z5)	4

As the algorithm is sorting the construction sequence by a bottom-up approach, it may only be viable for modular building elements with simplistic spatial relations. The construction order can be determined using a predefined construction schedule in 4D BIM. For each IfcElement, IfcTask and IfcRelAssignsToControl are attributed so that the algorithm can understand the predecessor of each step and validate the correct order during the construction stage.

While, iterative occurred during the system's development, demonstrating that the entire workflow was tested 5 times in front of a small audience from industry and academia. Although no strict scientific verification and validation methods were ready at the end of the semester project, the students were able to run the system two times successfully from start to end. Twice the students assisted by snapping an element (one floor and one wall element, in separate tests) into place with a very slight push of an index finger. Once the robot stopped after assembly the first design. The reason is still unknown. Yet, runtime data from the system was recorded during all test runs and is being processed at this time (and will be implemented in the final version of this paper).

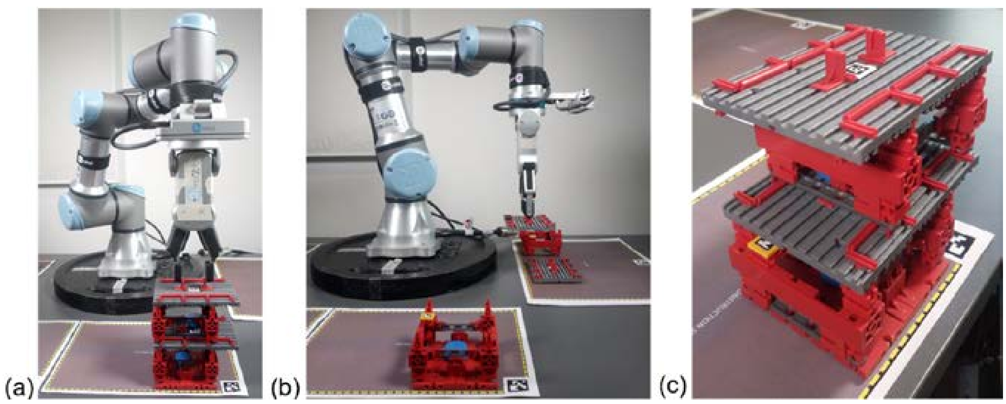

Fig. 8: Impressions from final demonstration exercises: Robot manipulator completing the fully-automated (a) assembly of the first modular building design, (b) disassembly and temporary storage, and (c) re-use of modular elements for assembly of second building design (manual selection, after disassemble).

4. CONCLUSIONS AND OUTLOOK

This work is the result of a semester-long study project that exposed four Masters-level students, one in architectural, one in civil, and two in mechanical engineering, to backgrounds that they had not learned before. For example, both the architectural and civil engineering student had no previous experiences with the field of automation and robotics, and likewise had mechanical engineering students neither a background in design or planning with 4D BIM nor any expertise in modular construction. The developed concept of a LFC has been partially validated, as the robot manipulator was able to follow a digital design and sequence to erect, disassemble, and rebuild a small-scale building while applying constraints that exist in a circular economy, for example, making as much use as possible of reusing building material. However, as observed, the limited project time that was given to the students restricted their curiosity in exploring additional research domains, for example, planning for alternatives, generative costing, digital twinning, and testing usability. In the future, a focus on qualitative and quantitative assessment methods must be set to evaluate both the students' and LFC's performances. Yet, the students' claimed new knowledge by applying their own expertise and discovering other fields. Furthermore, the experienced hands-on experiences with respect to realistic and still basic implementations of information modeling, computational coding, automation, and robotics, strengthened their learning. It is envisioned that the construction industry will benefit from students with such skill sets that a LFC is able to develop, share, or enhance. Yet, scaling up the developed concept of a LFC could yield future insights how digital building design can guide real-life automation and robotic applications in construction.

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IDENTIFYING AND DEVELOPING PREREQUISITES FOR TAKT PLANNING IN A BIM-BASED CONSTRUCTION PROCESS

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ABSTRACT: *The construction industry is undergoing a significant shift in how design and production are conducted. Building Information Modeling (BIM) has emerged as a key tool for coordinating information from all involved disciplines and providing a more holistic view of the construction process. However, effective coordination and communication between different professions remain major challenges that require new approaches to project management. Takt planning has gained increasing attention as a potential solution to improve traditional planning methods. Despite this, there is a lack of real-world studies exploring BIM and takt planning where information is structured according to takt planning. A takt planning structure for all BIM-models would bring a more holistic understanding of what is to be done, controlled, and reported back. To address this gap, this paper presents findings from a three-stage research process. Firstly, form a focus group of disciplines to find a shared structure to present the execution in a common way for design and construction in a lab environment at a conceptual level, secondly implementing it to the detailed design information for real -world case project in workshops and group meetings with the focus group and then thirdly, evaluate it in the case project with the site staff involved. The findings highlight the importance of a shared denominator to get a holistic approach to project management and enabling takt planning throughout all phases of construction, providing insights into its practical application and benefits for the construction industry.*

KEYWORDS: *WBS; Building information modeling (BIM); Project Management; Takt planning.*

1. INTRODUCTION

The construction industry is undergoing a significant shift in how design and production are conducted, this also affects how projects are documented and handed over once finished. This shift can be seen as a digital transformation, with a strong focus on technologies (e.g. Howard et al., 2002; Samuelson & Björk, 2014). A key in this transformation is the emergence of Building Information Modeling (BIM) for coordinating information from all involved disciplines and providing a more holistic view of the construction process (Azhar, 2011; Sacks et al., 2018). BIM can also alleviate information loss that occurs in conventional non-digital workflows (Borrmann et al., 2018, Chapter 1; Sacks et al., 2018). Thus, BIM is seen as a major contributor to the digital transformation of the industry (Samuelson & Stehn, 2023). While there are some projects moving from drawings towards a model-based construction and process (Disney et al., 2021; Gaunt, 2017), there is still a reluctance to fully adopt BIM and thus slowing change.

One factor identified as barrier to change is the fragmentation and high specialization of the construction industry, where a disconnect between design and construction phases contributes to the fragmentation (Cerezo-Narváez et al., 2020; Mohd Nawi et al., 2014), and the prevailing project conditions preserves roles, processes, value chains and working methods within individual companies and prevents change (Samuelson & Stehn, 2023). Traditionally, construction projects mostly follow a waterfall principle where information in each phase is adjusted and modified for respective phase (Leicht et al., 2020). Furthermore, the high fragmentation and specialization amongst subcontractors is identified as potential factor for projects overshot budgets and schedule overruns occur (Nepal & Staub-French, 2016). Work Breakdown Structure (WBS) can help in defining and structure the project (Makarfi Ibrahim et al., 2009). Cerezo-Narváez et al. (2020) stresses that by using a well-developed Work Breakdown Structure (WBS), that integrates the Cost Breakdown Structure (CBS), a more representative project schedule and budget can be produced, as well as project roles and responsibilities can be assigned to subcontractors more easily. Furthermore, Cerezo-Narváez et al. (2020) also emphases that there is a lack in alignment between WBS and CBS and that a more structured work management is essential, especially in the digital management of projects. Thus, a standardization of classifications could enable integration of the WBS and CBS and ensure a connected information flow. Jung and Kang (2007) notes that standardization of the WBS could contribute to a wide set of project control systems, such as scheduling, cost control, materials management amongst other construction business functions, this confirms similar conclusions shown in Garcıá-Fornieles et al. (2003), which also adds

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Efraim Ljung, Mikael Viklund Tallgren, Mattias Roupe, Mikael Johansson, *Identifying and Developing Prerequisites for Takt Planning in a BIM-Based Construction Process,* pp. 574-584, DOI 10.36253/979-12-215-0289-3.56

responsibility assignment and information management to the list. Therefore, there is a need to find shared information and classification structure to enable a flow of information from design to production and all the way to operations and maintenance (O&M). There is a lack of structuring of this in BIM data between different disciplines such as planning, scheduling and cost control (Cerezo-Narváez et al., 2020; Makarfi Ibrahim et al., 2009). Makarfi Ibrahim et al. (2009), concludes that a standardized WBS structure is missing and proceeds to develop and present a structure fitted to the UK construction sector, they also note limited possibilities for generalization of this structure worldwide and that WBS structures should be developed contextualized to respective market.

With regards to planning and control, standardized processes have been proven to be beneficial (Haghsheno et al., 2016), along with a BIM-model, the project can be divided into identifiable repetitions where Takt planning can aid in the communication and implementation of the schedule (Viklund Tallgren et al., 2022). With the rise of the use of BIM-models, research points towards a possibility to improve information flow between design and construction phases as well as improved communication and collaboration within phases, especially during planning and scheduling (Crowther & Ajayi, 2019; Nepal & Staub-French, 2016; Viklund Tallgren et al., 2021). However, there is a need for a more systematic approach to the coding of models to be able to use them throughout design and construction phases.

Thus, there is a need to support processes spanning over both design and construction, and through to O&M. Both internationally and nationally there are numerous examples on standards to address increased digitalization in construction, such as CoClass which is supposed to replace the older BSAB in Sweden, Cuneco Classification System in Dennark, Uniclass in the UK and the North American Architectural, Engineering and Construction industry system OmniClass for example (Cerezo-Narváez et al., 2020; Eckerberg et al., 2016). CoClass was developed to carry information about classes, properties and activities connected to different construction related processes. A sub-set of information created in one such process is a model view definition (MVD), governed by the information delivery manual (IDM).

Thus, the aim of this research is to investigate what information is needed for production control and management to integrate from the design phase to the construction phase and how this information should be structured to help understand the project and its challenges better. This paper proceeds with this question, and addresses the general question through the following research questions:

1. Which stakeholders need to be involved from design and construction phases to find a shared common information and coding structure?
2. What are the challenges with a shared information and coding structure for design and construction phases?
3. How are the developed shared information and coding structures utilized in an actual construction project?

This paper is structured as follows; a review of related works connected to WBS, classifications and planning is shortly presented, followed by an account of the results with regards to the research questions. As a result, from the focus groups a shared coding structure was identified that extends current classification. The discussion shows that the addition of deliverables and construction scope could be used throughout the phases of the project and was found to help communication between disciplines and construction phases. The findings highlight that this type of structured information enables the prerequisites needed to increase digitalization and integration between disciplines, enabling for example a more holistic Takt planning.

2. METHODS

This research uses a qualitative approach to explore the three research questions. A combination of methods has been used to gather data. A brief overview of these methods is followed by a more in-depth description later in this section. The research was instigated through an identification of the critical stakeholders to bridge the design phase and the construction phase. These stakeholders formed a focus group. The focus group combined workshops with focus group meetings to capture context and initial requirements for the information structure. These initial meetings informed the research and development process, and two additional stages were decided to be added. The second stage concentrated on implementing and evaluating information that formed the structure. The third stage expanded the group and focused on the effects of the proposed structure. The aim of the research was to investigate what information was needed for production control during the stages from design to construction and how this information should be structured to help understand the project and its challenges better.

The focus group meetings were documented with meeting minutes and field notes. Throughout the research one single project, Hovås Tak, was used as a case.

Fig. 1: The Hovås tak apartment project (Hovås tak, Nordr, 2022)

2.1 Case Study – Hovås Tak – An Apartment building

The project used in the research was an ongoing construction of an apartment building, located in southern Gothenburg, Sweden. The house is an apartment building with two co-joined tower-blocks forming a single body, se Fig. 1. Each stairwell has four apartments on each floor with a total of 59 apartments. The building has a total gross area of 5170 m^2 with a framing of precast walls and slabs, with light steel infill walls and a non-load bearing brick façade.

2.2 The three research stages

2.2.1 Stage 1: Identifying a Coding Structure and Required Information

There are a lot of people involved in a construction project, but not everyone has the same degree of influence on how the information is structured. In the case project, Hovås Tak project, the disciplines that account for the most decisive and or governing amount of information for the design and construction management were analyzed, and a focus group was formed with these disciplines to try to find a shared structure for the information.

The focus group of ten people was represented by following disciplines:

- Client – controls the vision, the purpose of the project and what is to be built. Control the names and designations of the different parts of the building as well as documents related to the project.
- Design manager and BIM coordinator – controls the information and information structure from the designers.
- Cost manager – advises over the content of the calculation and how it is structured.
- Scheduler – controls the structure of the schedule, the content is developed together with the site management.
- Site management (Project Manager, Site Manager, Site Engineer) – advises over construction planning, logistics, purchasing, site layout plan. (i.e., the overall structure of how the project will be executed, in the more detailed planning those involved in the module will be involved)

Through workshops, the focus group tried to find ways to group and or sort the information in a way that would primarily facilitate construction planning and scheduling. The workshops were used to define coding structure and the definition of the designations *"deliverables"* and *"construction scope"* used in the case project, Hovås Tak.

2.2.2 Stage 2: Implementing and Evaluating the Coding Structure and Information

The participants in the focus group were also active in the development of the detailed design documents. This took place in parallel with the second stage of the focus group workshops. The workshops also served the purpose to create consensus of the boundaries between the deliverables and the construction scope. The designations were documented continuously to create a uniform project language.

2.2.3 Stage 3: Effects of Using the Coding Structure

The construction documents were completed in Q1 2023, and construction started in early 2023. The focus group then begun to evaluate the effects of the developed shared information structure. The group also studied how the structure affected the understanding of the project documents and how the structure was used for the more detailed construction scheduling and documentation. An expanded focus group that also involved the main contractor, Skanska's entire site organization in the case project, Hovås Tak, was established, and in a workshop the group identified the changes brought about with the newly introduced coding structure.

3. RESULTS

The workshops and focus group meetings showed that the waterfall principle was used where the information structure is adapted to each discipline on the way downstream. Upstream traceability was secondary as the focus were identifying functional requirements and compiling the cost and steering towards the set budget. During this process, it was recognized that each discipline's description of the construction work was optimized for its discipline. The information was statically presented in the form of reports, drawings, and 3D models. The site management's planning during this stage was mostly highlighting, extracting relevant amounts of information to describe the step-by-step execution of the building via a detailed job planning description and assembly drawings.

The pre-manufacturing elements were manufactured from documents based on geometries and functional requirements that existed as construction documents. A disconnect were thus created between the created construction documents and the original design documents. Traceability backwards was secondary, and this made lessons learned more difficult to document. In comparison, digitization and model-based construction made the information less static, and the information could dynamically be presented/sorted in different ways to describe different purposes.

3.1 Stage one – Identifying Coding Structure and Required Information

During the workshops, the focus group began by clarifying the vision with the information, creating an aim and purpose for the information structure. Here, the client clarified the project vision for the case project, Hovås Tak. The client stressed that it should be a "*carefully planned and well-thought-out apartment building*". This influenced all the project communication and work processes.

The next workshop challenge was to find a consensus in the project designations. In the absence of clearly communicated names of the different parts of the building, prior projects have been shown that the different disciplines create their own designations to orient themselves. For the case project, a document was created to handle the project designations, and any revisions were logged in a similar way to a building document. The marketing team was represented by the client to ensure that a clear consensus was created in the designations towards end customers, facilities management, and O&M.

3.1.1 The disciplines different information structures in the case project

During the workshop it was identified that the model structure of the designers and the structure for material take-off both are linked to building parts and functional quantities. For the case project, Hovås Tak, the main contractor, Skanska's cost calculation structure and process is based on BSAB83 (Swedish classification system from 1983), and the BIM-model's structure is based on BSAB96 (Swedish classification system from 1996). The workshops concluded that the BSAB structure worked well for technically describing building components and functional quantities. Furthermore, the various contracts that were procured was based on similar groupings of functional requirements, so documentation for purchasing was relatively easy to filter out from the BIM.

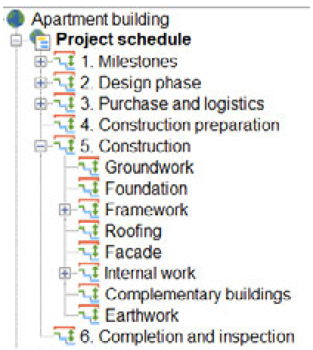

Fig 2: The schedule and time planning are based on the illustrated information structure.

The client's information structure was partly tailored for marketing to end customers and partly for O&M. The marketing material used the project designations when describing the final design of the building and the design and content of the different apartment types. The marketing language and information structure were adapted to attract the identified target customer group. O&M information was structured based on how the management of the property was planned. The client had a specific company-adapted structure for the facility management information which resembles a general BSAB structure.

The information structure of the scheduling is based on Skanska's basic scheduling template for housing projects see Fig. 2, which has been developed over the years and enables a rough comparison between projects. The site management together with a scheduler bases the schedule on this template structure and then details the phases to the specific project in accordance with the site management precious experience from similar projects.

Fig. 3: When having the same WBS and coding, it is possible to analyze projects KPI's against each other to find outliers.

For a number of years now, all housing projects at Skanska extract Key Performance Indicators (KPI) for cost and time according to crucial milestones – essentially a schedule plan analysis. The general phase schedule which is used as input for the analysis is shown in Fig. 3 (left), together with the project completion date KPIs plotted for a number of individual projects (right). By using the same general structure in all projects, it is thus possible to compare KPI metrics between different apartment building projects and identify outliers or projects that must be optimized when it comes to productivity. The case project, Hovås Tak, was analyzed using this specific structure to predict and forecast performance. As seen in Fig. 3 (right) the schedule analysis places Hovås Tak at the lower end of construction time, and at the mid-range for cost when compared to similar projects (i.e., as illustrated by the lower-left rectangle).

The Construction planning was then based on an execution structure (a step-by-step completion structure), for the project. The execution structure was based on Site layout plans for the general construction phases, the master schedule, logistics and delivery schedules and purchasing schedule.

3.1.2 Shared information structure

The information of each discipline was structured to describe their vital information in an effective way. A common denominator was identified as missing by the focus group. The denominator should enable grouping of information in a similar way regardless of discipline to coordinate a shared sequential execution The focus group decided to refine the basic schedule template and the schedule analysis together with the phases in the construction planning to create deliverables that group the information in a similar way for all disciplines.

A methodology for finding the shared information structure was developed. Through an iterative process where the first loop created the first overall names and a first overall division of the deliverables of the construction phases and its geographical division were adapted to the project's conditions and scope. A side effect of this work was that as more information was generated in the project, the focus group continually helped coordinate and structure the information to create consensus in project designations and construction phases, see Fig. 4.

CoClass was identified as a possible shared coding structure. However, suitable properties were missing to get a shared structure used by all disciplines.

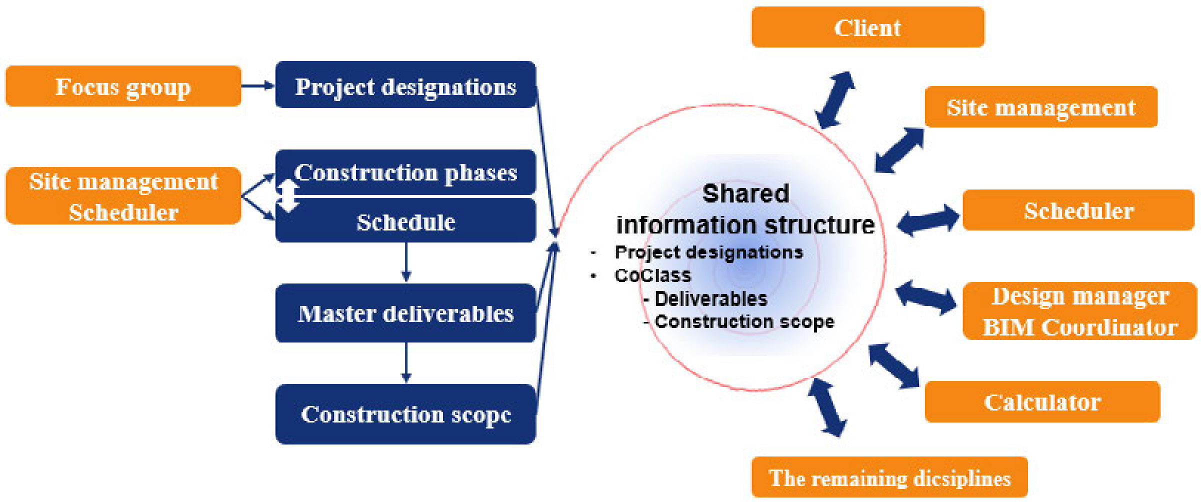

Fig 4: Illustration showing how a shared information structure for the construction project could support all the disciplines with CoClass coding of Deliverables and Construction scope.

In dialogue with Svensk Byggtjänst and the development team of CoClass, a contribution to the classification was made in the form of two new properties:

- Deliverables, "TPPR Produktions etapp" in Swedish, which is defined as a temporal object property indicating production phase.
- Construction scope, named "PRWT Produktionsdel", which can be defined as production property that specifies the spatial division of work.

By adding these two properties, the CoClass structure enables a shared structure to describe the project execution as well as the technical description for all disciplines. The case project, Hovås Tak, did not use CoClass to its full extents because existing coding structures were too tightly tied to the existing planning and cost management systems and their information structures, but the new properties were added to existing systems.

3.2 Stage two – Implementing and Evaluating Coding Structure and Information

By using storyboard form like film and sketching out a sequence of events for each construction phase, the focus group could agree on a more project-adopted division of the deliverables. The content of each deliverable was analyzed to ensure that the deliverables reflected and supported the actual execution. In particular, the focus group needed to discuss the transitions between the different deliverables for the information to be delimited in a similar way for all disciplines. The structure of the deliverables was then arranged in a hierarchy with a more comprehensive structure broken down into more detailed levels for certain deliverables where there was a need to describe the execution more clearly, see example in Fig. 5.

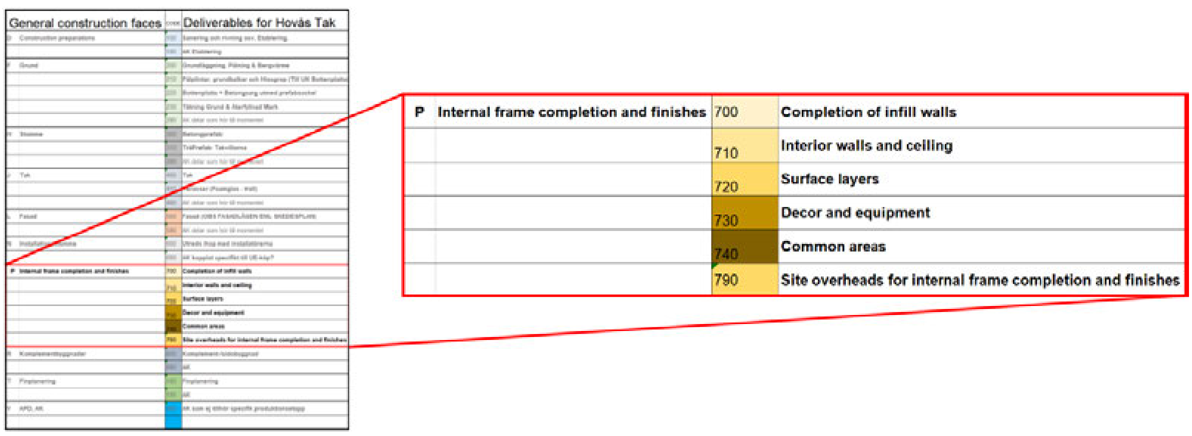

Fig. 3: Left part shows the general phases side by side with deliverables.

When the boundaries of the deliverables began to become clearer, the geographical distribution was analyzed to find a suitable material and workflow for each construction scope. This also had the effect that other disciplines could provide timely input to each other.

The construction scope was created to reflect the material flow to the specific location, the gradual execution of tasks within the scope, and provide structured information from construction for use during the O&M. Furthermore, digitization and model-based construction and takt-planning made the information less static and enabled filtering and sorting in different ways to describe different purposes.

3.2.1 Challenges

Both during design and cost management of the project the new coding structure posed challenges. In each phase it was found that the supporting systems did not easily allow mirroring of the execution process into deliverables. As a solution some composite model objects created from the classifications in the system were decomposed in more detailed functional parts to fit with the deliverables. A typical example is found in exterior walls for the case project. The design and cost management uses composite object to represent functional object of the exterior wall, meanwhile the schedule and the site management represents and complete the exterior wall in four different deliverables:

1. Construction framework,
2. Façade (external finishes),
3. Internal frame completion and
4. (internal) finishes.

While changing the systems for cost management and design was not a viable solution, a workaround was needed. This created extra administration in each discipline both in working with these WBS codes and filling them out and to work and ensure the quality of each discipline's own information.

3.3 Stage three – Effects of Using the Coding Structure

The first and foremost effect identified was the reduced language confusion in dialogue between the disciplines and how information was consumed between them. The disciplines experienced a reduced need to process and re-fit information in later stages of the construction process when the information was coded with deliverables and construction scope. By gathering construction results using this shared coding structure, a more holistic understanding of the project was formed by each discipline. Information that used to be found in different systems, sorted by different coding structures was now found more easily through the shared code structure. Additionally, disciplines could use the shared coding and information structure to ensure that they talked about the same deliverables and objects. Thus, communication between the design manager, BIM-manager, cost managers, the scheduler and site management could flow more easily.

Following are some distinct examples of how the shared coding structure simplified communication and where the combined information created more value than each piece of information on its own.

3.3.1 Schedule – presented in 3D model.

By connecting the deliverables of the models and the schedule and its construction scope, a visualization of the schedule was created directly using the BIM module in Powerproject. The visualization of the scope and content to be scheduled increased the understanding for the disciplines involved, and reconciliation of work completed became easier to review.

3.3.2 Upload quantity takeoff and easier cost control

Since the quantity takeoff from the model was already coded with deliverables and construction scope, time for the cost manager to structure the costing data was shortened. Changes in quantities were easier to identify by the focus group and updating the cost control was faster because a smaller amount of information had to be compared within a clearly defined area using the construction scope coding.

Since the cost estimate was able to be sorted based on how the case project, Hovås Tak, was to be executed, deliverables were faster reviewed and understood, and each sequence clearly visualized by the model using deliverables. The cost management could thus be linked to the degree of completion of each deliverable. Performance-based payment plans could also be linked to the work completed in each deliverable.

3.3.3 Quality work and inspection plan

The quality controls continued during the execution and ensured that the requirements were met in the finished product. With the help of the deliverables, quality risks for each deliverable could be identified. The monitoring of the inspection plan and self-inspections also became more clearly structured. The review of the inspection plan by the inspection manager together with the site organization and the various contractors was also greatly facilitated.

3.3.4 Work environment and safety risks

During the design phase, the principal designer is tasked with identifying work environment risks and as far as possible, eliminating them. The identification of work environment risks was facilitated by the simulation of the coordination of all discipline's BIM-models and construction phase schedules, gaining valuable insights into work environment risks needed to be considered in each deliverable.

3.3.5 Basis for takt planning

The sequential breakdown of the information, simulating the execution of the construction works were identified to be fully in line with the structure of the takt planning. One or more deliverables formed the basis from which work packages were created. The work packages could then be broken down into takt zones consisting of one or more construction scopes. This breakdown formed teams of disciplines that performed the work in each takt. The sequence of work in each takt zone formed a takt-train. All BIM-models follow this hierarchy and the addition of information and review of status of the BIM-model could be done continuously via each takt-wagon. By connecting the takt-planning with the model it was possible to dynamically filter and visualize the takt zones and takt-wagons for the different subcontractors.

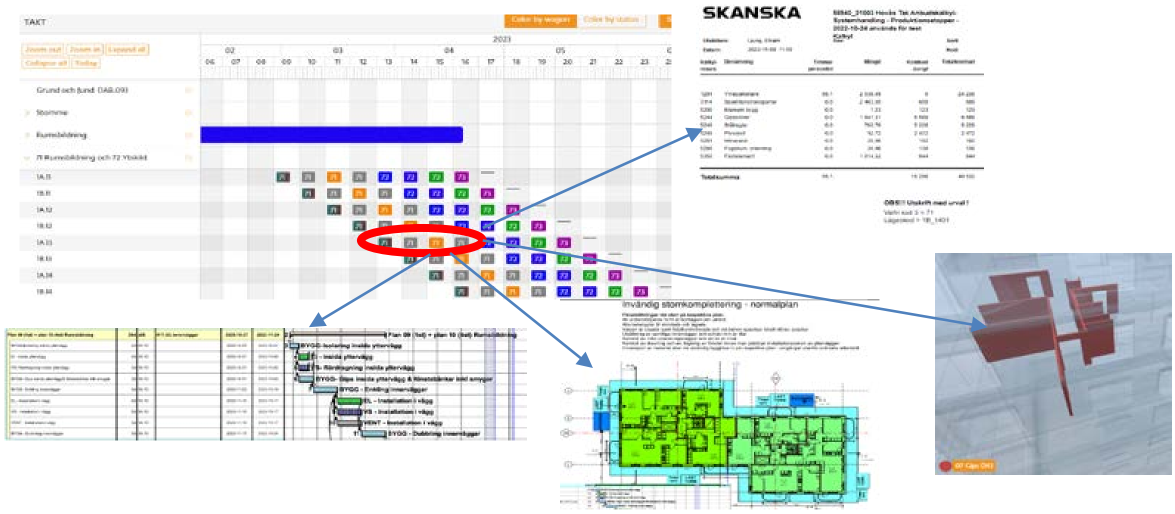

Fig. 4: By structuring of information in the project and BIM into shared code and information structure that supported and reflects how work progresses on-site, it was possible to connect the construction schedule, the cost control plan and takt schedule.

4. DISCUSSION AND ANALYSIS

The main insight during the focus group meetings were that a shared WBS and coding structure was lacking in the execution planning, similar insights has previously been presented but limitations in generalizability has been stressed (Cerezo-Narváez et al., 2020; Makarfi Ibrahim et al., 2009). Since the main contracting company recently has taken a more of a coordinating responsibility in new projects results show there is a great need to improve communication and coordination, similar conclusions are stressed in related studies (e.g., Crowther & Ajayi, 2019; Nepal & Staub-French, 2016; Viklund Tallgren et al., 2021). Thus, communication and coordination of subcontractors and designers, cost managers, schedulers and other stakeholders is as important for the project as it is for the site management.

The documentation of common language and designations eased communication process throughout the project. However, it could be argued that it is not necessary to replace the existing WBS and code structures that are well established for each discipline. The key is to bridge organization, process, technology, and information and through dialogue find common project denominators that enable the WBS and information to be grouped in shared way by different disciplines. This is supported by the conclusions and like the structure presented in Makarfi Ibrahim et al al., (2009), but customized and developed for the Swedish context. Deliverables and construction scope groups the project in ways that reflect how work progresses on-site and complements the traditional description of the construction results emphasized by existing coding structures and existing WBS systems.

The traditional segmentation of work in contracts, disciplines or functions will still be needed since each area has their own needs and demands on how to ensure quality of their information and optimize their work in their systems. The traditional division works well enough for optimizing purchases and clarifying responsibilities between contracts and disciplines. The added coding of deliverables enables a more pro-active and fine-grained analysis than previously was possible. Furthermore, a common WBS and information structure enables new possibilities to the development of schedule analysis and the KPI's on the master schedule critical path. This can give a deeper insight and understanding of how different projects progress and find outliers or inefficient projects. But this data could also be used in the future for machine learning and artificial intelligence during the bidding phase or planning of new construction projects.

Another outcome from the study was that the implementation by the focus group also improved the overall work processes, where the team came together and a closer bond was formed between design, cost management and site management, lowering the threshold for communication amongst them, in line with precious research (Crowther & Ajayi, 2019; Nepal & Staub-French, 2016; Viklund Tallgren et al., 2021). One of the main insights during the implementation of the developed WBS and coding structure was that the dialogue in the focus group was especially important to ensure that information from each discipline was coded in the right way. The presentation of the visualized sequencing through the BIM-model and the deliverables created a necessary foundation for the following dialogue between design, cost management and site management. This was seen in more open discussions between disciplines, enabled through the better understanding of the holistic view of the construction scope which is in line with previous research (Azhar, 2011; Sacks et al., 2018). The extra administration the respective disciplines experienced in the coding and its structure, is thus mitigated.

By moving from static information to a digital information structure enabled information to dynamically be sorted and grouped in new ways to better suit the needs of different stakeholders. Through this common WBS and information structure, a common ground was created adding flexibility to each stakeholders' specific needs, without affecting their basic needs. Thus, it could be argued that the process gave a better understanding how different parts and resources should work together to reach a better result in the project.

Since the production of the case project, Hovås Tak, started in January 2023, the production planning and implementation of the first production stages has been conducted and evaluated. An initial reflection is that even though the information more closely followed how the construction was conducted, it was difficult for the site management and workers to absorb the information in this new way, especially in the BIM system used. With everyone used to read static drawings and descriptions; new working processes and tools had to be introduced on site. A first step to implement the common WBS structure in the site organization could be to visualize the information in each deliverable in a workshop form and discuss on how to use the information from each discipline. This enables an identification of affected stakeholders and make them understand the scope of the project while together developing the detailed job planning and construction schedule. Thus, utilizing the benefits of involving the right stakeholders in the planning and scheduling, as seen in Viklund Tallgren et al. (2021).

The sequential division in different deliverables enables the construction team to focus on one thing at a time, thus ensuring that each deliverable reaches each respective goal, quality wise as well as budget wise and schedule wise. As the information is coded and structured in a way that easier enables the site management to sort and review information regardless of discipline, the site management is enabled to:

- Clarify the coordination of material flows and logistics for each deliverable.
- Clarify responsibilities connected to the project's execution as well as coordination of sequencing of the project in general as well as during takt zones.
- Clarify cost flows and performance-based payment plans sorted by deliverables.
- Create a good basis for quality control within each deliverable.
- Create a good basis for inspection rounds and follow-up of work done for deliverable.
- Create good structure for all types of implementation statistics such as work environment, deviations from initial project scope and schedule.
- Get a good structure for the collection of operation and maintenance data and a basis for as-built documentation.

Furthermore, the deliverables enable a standardization and identification of repetitions that also can form the basis for the takt planning, as highlighted in Haghsheno et al. (2016). In the case project, the deliverables were analyzed to build effective teams that work together to reach the common goal of the finished deliverable and where the construction scope was analyzed to create optimal takt trains. The common WBS structural hierarchy in deliverables and construction scope means that the information generated in the execution can be easily linked with the information sources (construction document, production estimates, schedules, and production planning such as purchasing and logistics). In a way the coding structure standardizes information expressed as missing in prior research (Cerezo-Narváez et al., 2020; Makarfi Ibrahim et al., 2009). Furthermore, the information gap between project stages indicated in Borrmann (2018) can be avoided in with the use of shared coding structures as brought forward in this research. Project documentation, facility management documentation and O&M instructions that normally tend to be based on how it was planned to be built and function, can now reflect as built.

Knowledge transfer with regards to finance, quality, productivity, becomes administratively simpler when all information is sorted with a shared structure and coordinated to get a better overall picture. The risk of some area being prioritized and the rest being suboptimized is then avoided.

Also, by using a common WBS and BIM-model in this way enables data-driven pro-active decisions throughout a project. This could in the future assist the construction industry with meeting climate objectives, where informed data-driven decisions reduce waste and lower the overall climate impact in the projects. Implementing WBS through BIM, with the support of other digital technologies can improve circularity assessments, increase material recycling and reuse, and more accurately track environmental data throughout a building's lifecycle all the way to decommissioning and dismantling of building.

Furthermore, this study and the developed WBS and information structure has contributed with input to the continued development of the Swedish classification system CoClass.

5. CONCLUSIONS

This paper presents a study of the design, development, and validation of a WBS and coding structure for supporting BIM and takt-planning in the context of a real construction project, Hovås Tak (case project). The aim has been to establish a shared information structure for all disciplines and investigate; what structure is needed for production control and management from design to construction and how this structure could help project management to understand the project execution and its challenges better. By structuring the WBS and its information in the BIM it was possible to support and mirror how work progress on-site. In this context, it was possible to connect the construction schedule, site management planning, the cost management, and the model of the project to a better holistic understanding. BIM enables the visualization of the step-by-step progression of the construction. Digitization and BIM enables detailed multidimensional WBS and coding, a shared code does not have to be governing, but a shared coding with lower common denominator can provide new interoperability opportunities between disciplines. Digitization, model-based construction makes the information less static and enables filtering and sorting BIM in different ways to describe different purposes. Furthermore, the common WBS and information structure is also an important base for a pro-active construction management and could be a base when it comes to takt-planning of the construction site and to gather information to the digital twin.

6. ACKNOWLEDGEMENT

This work is part of the Digital Twin Cities Centre and funded and supported by Sweden's Innovation Agency Vinnova under Grant No. 2019–00041 and by SBUF Grant No. 14237 (Development Fund of the Swedish Construction Industry) and CMB (Centre for Management of the Built Environment).

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FCM-ENABLED APPROACH FOR INVESTIGATING INTERDEPENDENCIES OF BIM PERFORMANCE FACTORS IN THE SUSTAINABLE BUILT ENVIRONMENT

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ABSTRACT: *In pursuit of a sustainable built environment, BIM plays a crucial role in the project's performance and has egressed as a powerful technology in the construction industry, impacting the outcome and the project delivery workflows. Numerous dynamic and interdependent factors influence BIM performance. However, Existing literature prominently focuses on exploring the influencing factors for BIM performance, ignoring the impact and strength of the interplay of these factors on one another, therefore offering an inadequate picture of optimizing BIM performance. The evolving nature and degree of complexity of construction projects necessitate the identification and comprehensive understanding of the interdependencies between factors contributing to BIM performance in the sustainable built environment. A Fuzzy Cognitive Map (FCM) is a modeling method that represents and analyses the interplay between the factors in a complex system. So, this study proposes an FCM-enabled approach to investigate the interdependencies of factors contributing to BIM performance and conduct what-if scenarios, including predictive analysis. The developed FCM model can help reveal the hidden cause-effect relationships among a complex system of BIM performance factors, enabling stakeholders to develop more informed strategies and proactively plan to optimize BIM Performance.*

KEYWORDS: *BIM performance, Fuzzy Cognitive Map (FCM), Built environment*

1. INTRODUCTION

Sustainable development has become the crucial state that all sectors aim to achieve, and the built environment is no exception. Sustainable development implies balancing human socioeconomic activities and the natural environment's capacity to provide resources and absorb waste on a global scale. In pursuing sustainable development, delivering construction projects with improved performance to achieve sustainable goals shall play a significant role. Studies in the literature have shown several factors influencing project performance. Chang et al. (2017) explored the factors that influence project performance and highlighted the technological aspects that significantly affect project performance, pushing stakeholders towards adopting the technology in the built environment. Building Information Modeling (BIM) has emerged as a promising digital technology in the AEC sector, enabling the ability to enhance performance in areas including design, procurement, prefabrication, construction, and post-construction(Wang et al., 2022). Although the BIM concept dates back to the 1970s, the adoption of the BIM was seen as significantly increasing since 2000 (Caglayan & Ozorhon, 2023). Effective adoption and continuous performance improvement of BIM requires maximizing the benefits and high exploitation of the capabilities of BIM, further pushing stakeholders to gain a holistic approach and a deep understanding of the dynamics of the influencing factors. Several studies have been conducted on BIM adoption and assessing its performance in various project phases, including design and construction. However, BIM performance is not an isolated aspect. Moreover, inefficiencies are caused by the influence exerted not by discrete factors but by the amalgamate impact of the combination of dynamically connected factors in construction projects. Therefore, identifying the causes of inefficiencies also becomes crucial (Zhang et al., 2021) to improve BIM performance. While existing studies have made momentous strides in identifying factors that influence BIM performance, there is a noticeable gap in understanding the dynamics between the factors whose influence propagates throughout the system of the construction project and eventually impacts the BIM performance. This study attempts to address this noticeable gap by proposing a Fuzzy Cognitive Map (FCM) model to explore the intricate mechanism of dynamic interconnections among the factors that influence BIM performance. The study aims to identify the factors (individually or in combination) causing inefficient BIM performance and provides a dynamic model that can be used to simulate the propagation of influence caused by policy modification through FCM theory.

2. LITERATURE REVIEW

2.1 BIM Influencing Factors

BIM has been extensively studied in the research community, attributed to its positive impact on project

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Pavan Kumar, Aritra Pal, Yun-Tsui Chang, Shang-Hsien Hsieh, *FCM-Enabled Approach for Investigating Interdependencies of BIM Performance Factors in the Sustainable Built Environment,* pp. 585-593, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.57

performance. Several studies have been looking into the factors that impact BIM adoption and its performance. These factors are often called critical success factors, or risk factors, or key performance indicators (Caglayan & Ozorhon, 2023). Rogers et al. (2015) investigated the factors driving BIM adoption for engineering consulting services (ECS) in the Malaysian construction industry. Inadequacies of BIM experts, guidance, and government support were found to be hurdles for the ECS. Lee et al. (2018) Propose an innovative trust-centric contracting model to enhance BIM performance within Engineering, procurement, and construction (EPC) projects and explain trust's positive influence on BIM performance. Caglayan & Ozorhon (2023) propose a framework to determine BIM effectiveness and identify the project, industry, and company-based factors influencing BIM effectiveness. Project and company-based factors were identified to govern the BIM effectiveness. Badrinath et al. (2018) propose an empirical methodology to explore the factors for successful BIM projects and identifies highly governing factors groups such as the BIM technology, stakeholder skills, and competencies. Several studies have examined BIM performance and attempted to explore the influencing factors to exploit the full potential of BIM. However, the studies in the literature rarely considered the system complexity and dynamics of the interactions among the factors, ignoring the causal propagation of impacts of any discrepancies of influencing factors. Furthermore, inefficiencies are caused by various degrees of influence by factors. Hence, identifying and eradicating those causes are significant in preventing inefficiencies (Zhang et al., 2021). This necessitates analyzing the dynamic relationships among factors influencing BIM performance. Luo et al. (2022) highlighted several static methods available to study the influencing factors, such as the Fuzzy analytical hierarchy process (FAHP) and Fuzzy analytic network process(FANP), However, these methods pay little to no attention to the dynamic interaction and complexity of the system. Hence, this study employs the FCM method to investigate the dynamic interactions among BIM performance factors and aims to identify factors causing inefficiencies in BIM performance.

2.2 FCM Approach

FCM was introduced by Kosko (1986) to model and simulate dynamics systems. FCM helps mimic a complex system by considering the causal relationships between the concepts (Poczeta et al., 2020). It is a powerful method that can simulate the interaction of factors. FCM enables the systematic propagation of causal relationships between the factors, hence a suitable and systematic decision approach for analyzing and deriving insights into complex system performance (Zhang et al., 2021). Luo et al. (2022) used FCM to explore the dynamic relationship between influencing factors and prefabricated building cost, further, employed FCM to identify the root causes and sensitivity of factors to conclude that the scale effect has the greatest effect on the prefabricated cost. Zhang et al. (2021) employed the FCM method to measure the Tunnel Boring Machine (TBM) performance and conduct root-cause analysis and what-if scenario to explore the dynamic relationship between the factors that influence the TBM performance. Case et al. (2018) examine the application of FCM in modeling construction management problems and project complexities and details the construction of FCM models for construction management problems. Luo et al., (2020) propose a novel hybrid approach that combines the structural equations model (SEM) and FCM to examine the impacts of discrepancy in project complexity on the project's success. Luo et al. (2022) compared the four typical methods that are used for the simulation of the interaction between the factors.

3. METHODOLOGY

The methodology of this research involve FCM-enabled predictive analysis for BIM performance and consist of identifying concepts, determinination of relationships, and FCM computation and analyzing, as described in the following subsections.

3.1 FCM Development and Computation

3.1.1 Identification of Concepts

Identification of the concepts provides the basic structure for the FCM. FCM consists of several concepts, often called nodes or factors, referring to variables, elements, or attributes mimicking the various aspects of the system. Zhang et al. (2021) highlight the sources for identifying concepts such as accepted knowledge from the domain, empirical knowledge, and domain experts. Figure 1 illustrates a simple FCM model. These concepts (C_i) are connected by directed arcs, often called connections or edges, to represent the causal linkage between the concepts. Every concept in the FCM model bears a value ranging from 0 to 1 (Poczeta et al., 2020).

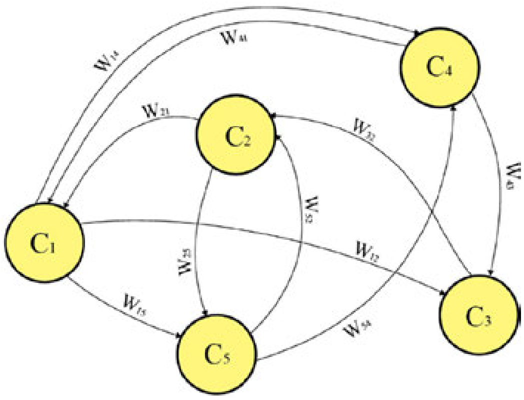

Fig.1. Illustration of simple FCM

In this study, BIM performance influencing concepts are derived through a literature review and further reduced and added after a brainstorming session with experts. Finally, 18 BIM performance controlling concepts are finalized. Concepts include BIM knowledge of the project participants (C_1), BIM training (C_2), BIM motivation (C_3), Consistent views on BIM between stakeholders (C_4), Top management support/BIM leadership (C_5), Project delivery methods encouraging collaboration (C_6), Collaboration and communication (C_7), Change management (C_8), Project complexity (C_9), Availability of BIM guidelines/protocol (C_{10}), Provisions in contracts on data security (C_{11}), Provisions in contracts on liability & risk (C_{12}), Provisions of agreed standard of rules to protect the BIM employees (C_{13}), BIM execution plan (C_{14}), Hardware and software infrastructure (C_{15}), The capability of hardware and software infrastructure (C_{16}), Information Quality (C_{17}), BIM experience of the stakeholder's company (C_{18}) and BIM Performance (C_T). The descriptions of concepts are described in Table 1.

Table 1. Concept identification for BIM Performance.

ID	Concept	Description	Reference
C_1	BIM knowledge of the project participants	Competence of project participants in using BIM tools and methodologies.	(Caglayan & Ozorhon, 2023)
C_2	BIM training	Training programs to develop BIM-related skills and knowledge among project participants.	(Einur Azrin Baharuddin et al., 2019)
C_3	BIM motivation	Incentives and drivers for project participants to adopt and implement BIM.	Suggested by expert
C_4	Consistent views on BIM between stakeholders	Alignment and agreement among stakeholders on the goals and benefits of implementing BIM.	(Al-Mohammad et al., 2023)
C_5	Top management support/BIM leadership	Endorsement and active support from top-level management for successful BIM implementation.	(Caglayan & Ozorhon, 2023)
C_6	Project delivery methods encouraging collaboration	Project delivery method facilitating better collaboration among stakeholders (for example, integrated project delivery).	(Salim & Mahjoob, 2020)
C_7	Collaboration and communication	Effective collaboration and communication processes among project participants using BIM.	(Oraee et al., 2019)
C_8	Change management	A systematic approach to managing and implementing changes associated with BIM adoption.	Suggested by expert
C_9	Project complexity	Level of complexity and size of the construction project.	(Jiang et al., 2021a)

C_{10}	Availability of BIM guidelines/protocol	Internal guidelines/protocols for consistent BIM implementation in the project.	(Al-Mohammad et al., 2023)
C_{11}	Provisions in contracts on data security	Provisions in contracts addressing data security, privacy, and confidentiality in BIM projects.	(Al-Mohammad et al., 2023)
C_{12}	Provisions in contracts on liability & risk	Provisions in contracts addressing liability and risk allocation for stakeholders in relation to BIM implementation.	(Al-Mohammad et al., 2023)
C_{13}	Provisions of agreed standard of rules to protect the BIM employees	Agreed standards of rules protecting the rights and liabilities of individuals involved in BIM projects.	(Al-Mohammad et al., 2023)
C_{14}	BIM execution plan	A comprehensive plan outlining BIM implementation strategy, processes, and deliverables.	(Franz & Messner, 2019a)
C_{15}	Hardware and software infrastructure	Adequate hardware and software resources for BIM implementation.	(Al-Mohammad et al., 2023)
C_{16}	The capability of hardware and software infrastructure	BIM software capability to meet project requirements, handle complex geometries, and more. (interoperability)	(Al-Mohammad et al., 2023)
C_{17}	Information quality	Accuracy, completeness, and reliability of information within BIM models and datasets.	(Song et al., 2017)
C_{18}	BIM experience of the stakeholder's company	Level of experience and familiarity with BIM technologies and processes within the company.	(Caglayan & Ozorhon, 2023)
C_T	BIM Performance	Effectiveness of BIM adoption and utilization in a project, aiming to maximize efficiency, return on investment, and harness the full potential of BIM across all project phases.	(Caglayan & Ozorhon, 2023)

3.1.2 Identification of causal relationship and computation

The concepts are linked by causal relationships. The direction of the causal relationship is represented by the connections or arcs describing the degree of influence between the concept C_i and C_j, often referred to as weights (W_{ij}) (S. Lee et al., 2004) that can be positive or negative, with values ranging from -1 and +1. In the complex system, in the case of any variation in the state of C_i results in a variation in the state of C_j, the arc is used to represent the causal relationship between C_i and C_j. $W_{ij} > 0$ represents the increase or decrease in the C_i leads to an increase or decrease in C_j, respectively, while $W_{ij} < 0$ represents an increase or decrease in C_i leads to a decrease or increase in C_j, respectively. Furthermore, if the W_{ij} equals zero, it indicates the absence of a causal relationship(Maitra & Banerjee, 2014). Identification of the causal relationship is the key component of building a FCM. Luo et al. (2022) highlight the two approaches to determine the degree of causal influence between the concepts, such as the learning method, which demands a large number of historical data, and the expert method. This study employs expert methods and uses fuzzy semantics to describe the degree of causality among concepts using nine levels of fuzzy semantics such as negatively very strong, negatively strong, negatively moderate, negatively weak, neutral, positively weak, positively moderate, positively strong, positively very strong with membership vales as -1, -0.75, -0.50, -0.25, 0, 0.25, 0.50, 0.75 and 1 respectively.

Causal interconnections of the FCM are mathematically presented by the n x n matrix(Zhang et al., 2021), and the state value of concept C_i at the time t+1 can be obtained through the following equation (Stylios & Groumpos, 2004)

$$A(t+1) = f\left(A_i(t) + \sum_{j=1, j\neq i}^{n}\left(W_{ji} \times A_j(t)\right)\right) \quad (1)$$

where $A_i(t+1)$ represents the state value of the concept of C_i at time t +1 as $A_i(t)$ and $A_j(t)$ represents the state value of concept C_i and C_j at time t, respectively.

Two types of threshold functions are employed in the FCM framework, i.e., sigmoid and hyperbolic tangent functions.

$$f(x)=(1/(1+e^{-cx})) \quad (2)$$

$$f(x)=\tanh(x)=((e^{x}-e^{-x})/(e^{x}+e^{-x})) \quad (3)$$

Eq. (2) is employed to map values between 0 and 1, whereas Eq. (3) is employed to map the values between -1 and +1 (Zhang et al., 2021). In dynamic FCM models, usually, the connection values range from -1 and 1(Barbrook-Johnson & Penn, 2022). In this study, experts' responses on causal relationships are taken in the range of -1 and 1 to understand the dynamic interaction between the influencing BIM factors. Hence we choose the hyperbolic tangent function [Eq. (3)]

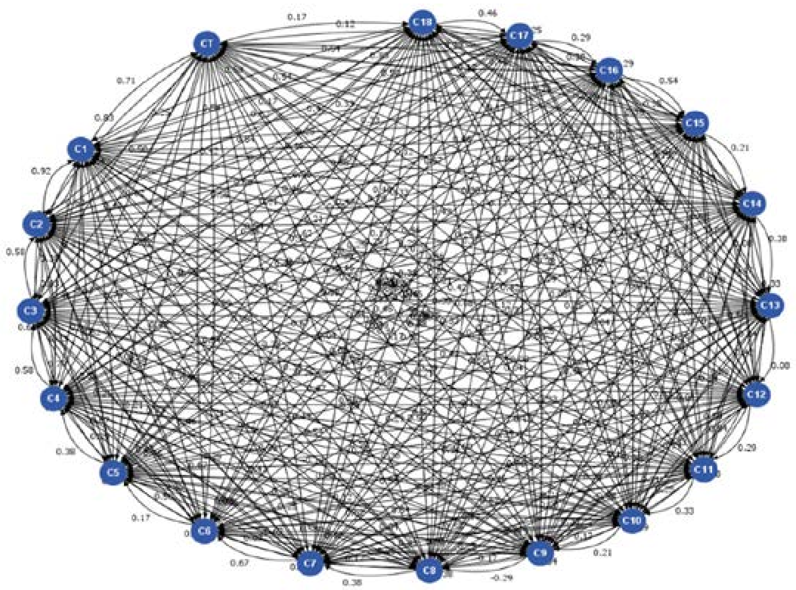

Fig. 2. Fuzzy Cognitive Map of BIM Performance

The responses of a totally 6 experts from India and Taiwan were received for the questionnaire and respondent background is shown in Table 2. The answers from the experts are further complied to calculate the weight for each concept by the center of gravity (COG) method. For example, W_{1T} is aggregated to be 0.71 as three experts rated positively strong, two experts rated positively moderate, and another rated positively very strong.

Table 2. Expert's background

Respondent	Professional background	Educational background
Expert 1	BIM Manager	Master
Expert 2	Researcher	Doctor
Expert 3	BIM Manager	Master
Expert 4	BIM Engineer	Bachelor
Expert 5	BIM Manager	Master
Expert 6	BIM Strategist	Doctor

There are several tools to facilitate the development of the FCM model. Nápoles et al. (2018) identified and compared several FCM tools and proposed a tool called FCM Expert, which facilitates adequate graphical support and higher experimental options. In this study, FCM Expert tool is employed, considering its advantages of FCM Expert over other tools. Creating the concepts and assigning aggregated weights to the concepts, results in the FCM model of BIM performance that is graphically presented in Fig. 2. FCM facilitates to simulate the behavior of systems and enables the what-if experiments (Papageorgiou & Salmeron, 2013). In order to identify the concepts influencing BIM performance, considering the dynamic interplay among the concepts, FCM, once modeled, allows the predictive analysis.

3.2 Predictive Analysis and Discussion

FCM-enabled predictive analysis facilitates the forecast of the outcome or impact of a cause when information or evidence of the cause is available (Zhang et al., 2021). It allows to curate the experiments involving simulation of impacts of the target variable (C_T) when evidence of change is available in the influencing variables (Luo et al., 2022). To address the uncertain nature of the concepts, a five-point linguistic scale: very favorable, favorable, neutral, unfavorable, and very unfavorable, with numerical values as 1, 0.5, 0, -0.5, and -1, respectively. The dynamic propagation of the effect of change in nature (very favorable, favorable, neutral, unfavorable, and very unfavorable) of influencing concepts (C_1 to C_{18}) on CT in a system of network simulated and the effect of the target variable (C_T), i.e., BIM Performance is observed. For example, the initial nature of all the concepts is set to neutral except C_9, whose nature is assumed to be very favorable, favorable, unfavorable, or very unfavorable, to observe the effect on BIM Performance (C_T) until it stabilizes. Table 3. Presents the stable values of CT after a set of iterations in different values (1,0.5, -0.5,1) of C_1 to C_{18}. For example, the stable value of C_T when C_1 is very favorable (=1) is 0.948, implying a positive correlation between C_T and C_1. All the concepts except C_9 tend to have a positive correlation with the target variable, i.e., BIM Performance. The stable value of C_T when C_9 is very unfavorable (=-1) is 0.951, implying the negative correlation between them. Fig.3 illustrates the impact of the concepts C_1 and C_9 on C_T. Predictive analysis results showed that concepts C_1 (BIM knowledge of the project participants), C_2 (BIM training), C_9 (Project complexity), and C_{14} (BIM execution plan) have a high influence on BIM performance. Similar results are demonstrated by other studies, such as Caglayan & Ozorhon, (2023) demonstrate that project-based factors such as BIM training and BIM knowledge of the individuals on the BIM project have a direct impact and great influence on the effectiveness of the BIM. Project complexity (C_9) has a significant impact on BIM performance. The negative correlation here implies poor BIM performance resulting from the combination of the influence of BIM knowledge and training. Jiang et al. (2021b) study BIM performance, project complexity, and user satisfaction and highlight project complexity as the key factor for BIM performance and user satisfaction. Furthermore, Franz & Messner, (2019b) shows the positive impact of the BIM execution plan, not only on participating members but also the performance. Similarly, the results of predictive analysis tend to show the positive influence of the BIM execution plan (C_{14}) on BIM performance. The predictive analysis aids the deeper understanding in enhancing the effectiveness of BIM adoption and aiming to use the full potential of BIM.

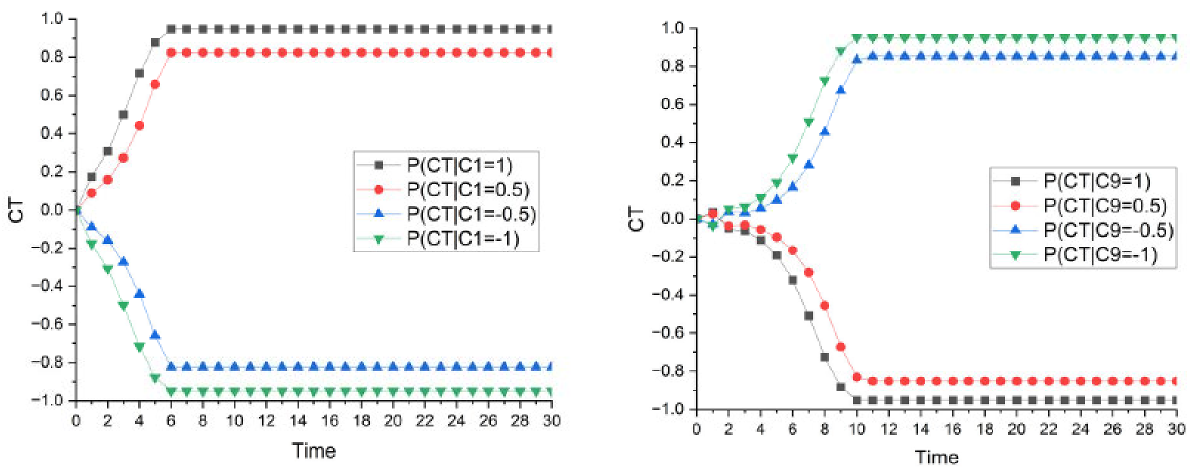

Fig.3. Impact of concepts C_1 (BIM knowledge of the project participants), C_9 (Project complexity) on C_T (BIM Performance)

Table 3. Stable values of C_T under different scenarios

Concept ID	$Ci = 1$	$Ci = 0.5$	$Ci = -0.5$	$Ci = -1$
C_1	0.948	0.823	-0.823	-0.948
C_2	0.942	0.839	-0.839	-0.942
C_3	0.811	0.621	-0.621	-0.811
C_4	0.830	0.682	-0.682	-0.830
C_5	0.835	0.689	-0.689	-0.835
C_6	0.890	0.747	-0.747	-0.890
C_7	0.911	0.793	-0.793	-0.911
C_8	0.942	0.808	-0.808	-0.942
C_9	-0.951	-0.832	0.832	0.951
C_{10}	0.892	0.763	-0.763	-0.892
C_{11}	0.780	0.611	-0.611	-0.780
C_{12}	0.690	0.609	-0.609	-0.690
C_{13}	0.780	0.619	-0.619	-0.780
C_{14}	0.979	0.900	-0.900	-0.979
C_{15}	0.849	0.721	-0.721	-0.849
C_{16}	0.908	0.790	-0.790	-0.908
C_{17}	0.940	0.807	-0.807	-0.940
C_{18}	0.903	0.788	-0.788	-0.903

4. CONCLUSION

BIM adoption and enhancing its performance in construction projects is a complex system where several factors influence its effectiveness in exploiting the high potential of BIM. It is crucial to pinpoint the factors causing the strong influence on BIM performance, considering the dynamic relationship among them. FCM models are better suited to explore and reflect the cause-effect relationship among the concepts (Luo et al., 2022). FCM's approach to understanding the dynamic relationship between factors that influence BIM performance is suitable due to its dynamic complexity. Furthermore, it allows predictive analysis to forecast the behavior of the network of the system. The concepts for the BIM performance were identified from the literature and further filtered through brainstorming sessions with experts to finalize 18 concepts. Relationships between the concepts were captured through a survey, and FCM was developed to enable predictive analysis. The results showed a high positive influence from the concepts: BIM knowledge of the project participants (C_1), BIM training (C_2), and BIM execution plan (C_{14}) have a big influence on BIM performance, whereas Project complexity (C_9) tend to show the negative correlation implying the special precautions to be taken by stakeholders to enhance the effectiveness of the BIM adoption to leverage the full potential of BIM in high complexity in the construction project.

In the course of this study, highlighting encountered limitations shall aid the improvement in future studies. The factors identified for the study are pivotal for exploring the dynamic interaction among the BIM performance influencing factors and are not extensive. Additionally, the reliability of the FCM employed could be strengthened with high responses and the widespread input of experts.

The exploration of the relationships among the factors is enabled through several methods, as mentioned before. However, understanding the dynamic relationship among them and the propagation of ripple effects among the network system is better understood through adopting less static models like FAEM and FMEA. In order to capture the dynamic complexity, the systems thinking approach can be used to understand the behavior of the system of BIM and assess BIM's performance with higher experts' involvement. To date, several construction activities are highly dependent on the experience of the experts; the FCM can be used to capture crucial human knowledge in the context of effective BIM adoption to aid better decision-making for the stakeholders involved.

ACKNOWLEDGMENT

This research has been supported by the Ministry of Science and Technology, Taiwan, with grant MOST 111-2923-E-002-010-MY3.

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A ROBOTIC METHOD TO INSERT BATT INSULATION INTO LIGHT-FRAME WOOD WALL FOR PANEL PREFABRICATIONS

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ABSTRACT: *Currently, industrial robot arms are trending in prefabricated building construction; however, a notable gap exists in established automated processes and related research specifically for the insertion of batt thermal insulation. The current method for accomplishing this task relies on manual insertion, which is labour-intensive for the workers and poses long-term health and safety concerns. This research presents an ongoing research project aimed at developing a feasible robotic process for the automated insertion of batt thermal insulation into prefabricated light-frame wood wall frames. This research focuses on the utilization of a single 6-degree-of-freedom robot arm for the insertion process, complimented by the design of a custom-built end-effector. The proposed robotic insertion process, named GLITPP, comprises of six major steps: (1) Grasp, (2) Lift, (3) Insert, (4) Tilt, (5) Push, and (6) Press. The GLITPP insertion process, along with the custom-built end-effector effectively mitigates the influence of the insulation's nonlinear mechanical properties, while also taking collision avoidance into consideration. This ensures a tight-fitting insulation within the frame cavity, without visible gaps and deficiencies. The necessary physical operating parameters for the insertion process, such as angles, offset, and force requirements, are identified to ensure the precision, efficiency, and repeatability of insertion. A prototype of the designed end-effector is used to demonstrate and validate the robotic method, achieved a high success rate of 93.3%. The development of this research will further advance the complete automation of light-frame wood wall panel prefabrication, offering the industry a wider range of options for selecting thermal insulation for their processes.*

KEYWORDS: *Robotic Building Prefabrication; Robotic Insertion; Light-frame Wood Construction; Robotic End-effector; Automation in Construction; Thermal Insulation*

1. INTRODUCTION

Industrial robot arm technology is increasingly being demonstrated and utilized in building construction processes due to its cost effectiveness, ease of programmability, high accuracy, and capacity (Chai et al., 2022; Koerner-Al-Rawi, Park, Phillips, Pickoff, & Tortorici, 2020; Leung, Apolinarska, Tanadini, Gramazio, & Kohler, 2021). Robot arms support mass production due to their high efficiency in performing repetitive tasks and their scalability, making them particularly suitable for the construction of prefabricated modular light-frame wood wall panels. These panels are prefabricated offsite, incorporating essential building elements such as framing, insulation, and sheathing. The use of robotic arms for cutting, assembling, and nailing timber for framing and sheathing is already well established and utilized (Stricot-Tarboton, 2019).

Various insulating materials are available on the market for timber framed structures, but the common types include blow-in insulation, spray foam insulation, and batt thermal insulation, made from fiberglass or mineral wool. Among these, batt thermal insulation holds a dominant market position due to their low cost to effective thermal performance ratio (Latif, Bevan, & Woolley, 2019). Currently, the automated insulation installation solution used to support the construction of modular light-frame wood wall panels are blow-in insulation (Orlowski, 2020) and spray-foam ("SprayWorks Equipment" n.d.; "Spray-R" n.d.), due to their loose form and ability to easily conform to voids. However, batt thermal insulation still needs to be manually installed by workers in the light-frame wood wall panel construction process (Stricot-Tarboton, 2019), which hinders achieving a fully automated construction process using this type of insulation.

The mechanical behaviors of batt insulation made of either mineral wool or fiberglass are classified as semi-rigid and non-rigid, respectively. In terms of mechanical properties, both these insulations are considered anisotropic deformable materials due to random fiber orientation. The result is that the rigid body assumption cannot be employed. In addition, predicting deformation and deflection of insulation using classical approaches is insufficient. Furthermore, the relationship between stress and strain is nonlinear thus complicating the modelling

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Xiao Han, Cheng-Hsuan Yang, Yuxiang Chen, Alejandra Hernandez Sanchez, *A Robotic Method to Insert Batt Insulation into Light-Frame Wood Wall for Panel Prefabrications,* pp. 594-604, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.58

process which has downstream effects on simulation and analysis. To the best of our knowledge, there has been no formal study or research on the robotic process of inserting anisotropic deformable material into a shallow cavity for a tight-fit. Manipulating deformable objects presents challenges as classical analytical force relationships are no longer applicable. Consequently, predicting and controlling material behavior during manipulation requires complex contact analysis and modeling of nonlinear material behavior (Arriola-Rios et al., 2020; Zaidi, Corrales, Bouzgarrou, Mezouar, & Sabourin, 2017).

The successful development of this research will allow for direct integration into existing prefabricated modular light-frame wood wall panels construction processes to realize full automation or prefabricated construction using batt thermal insulation. The implementation of this automated process offers several benefits, including the elimination of risks to workers from developing chronic respiratory diseases due to exposure to airborne dust and fibers, as well as reducing their exposure to carcinogens and volatile organic compounds. Additionally, it will decrease the ergonomic risk arising from repetitive movements during manual insulation installation. (BREUM, SCHNEIDER, JØRGENSEN, VALDBJØRN RASMUSSEN, & SKIBSTRUP ERIKSEN, 2003; Kupczewska-Dobecka, Konieczko, & Czerczak, 2020; Li, Han, Gül, & Al-Hussein, 2019).

This paper is structured into six sections. Section 2 introduces the research objectives. In section 3, the design concept of the robotic end-effector and robotic insertion process are explained. Section 4 covers the implementation and parameters identification. Following that, Section 5 presents the outcomes of the conducted experiments, providing an in-depth analysis of the results. Lastly, Section 6 presents our conclusions and outlines potential avenues for future research and development.

2. RESEARCH OBJECTIVES

This research aims to develop a robotic method to automatically insert batt thermal insulation into a light-frame wood wall frame. Studies have been conducted to explore the process of utilizing industrial robot arms to insulate wall panels through blow-in insulation and spray foam insulation methods. However, the utilization of robotic methods for inserting batt insulation has been rarely discussed. When implementing the robot arm for batt insulation insertion, the most critical challenges are effectively manipulating deformable materials, along with ensuring collision-free trajectories for the robot arm. To achieve the goal of automatically inserting batt thermal insulation using robotic methods, the objectives of this research will focus on the following:

1. Designing a robotic end-effector capable of proficiently manipulating batt thermal insulation, while considering its geometrical properties and deformable material behaviors.
2. Developing a robotic process for inserting batt thermal insulation into light-frame cavities using the proposed robotic end-effector to mitigate the influence of the deformation uncertainties and nonlinear mechanical properties.
3. Identifying variable parameters (e.g., angles, location, forces, etc.) of the developed robotic process to ensure the integrity and success of insertion and to minimize potential collisions.

3. ROBOTIC END-EFFECTOR & INSERTION PROCESS DESIGN

The developed robotic method contains two major parts: the robotic end-effector and the robotic insertion process. First, to facilitate the pickup and manipulate batt insulation to correct positions, a dedicated robotic end-effector was designed. Then, a robotic insertion process with six major steps was developed to effectively insert the batt insulation into the light-frame.

3.1 Assumptions

The developed robotic insertion process is based on the following three assumptions:

1. The light-frame wood wall is a typical straight wall without any piping or wires within the cavity.
2. The wood stud utilized in the frame is in a favorable condition, with negligible warping.
3. The working platform features a smooth surface, and the friction between the insulation and the working platform is considered negligible.

3.2 Robotic End-effector Design

Illustrated in Figure 1, the end-effector comprises four components: a two-finger gripper, a force-torque sensor, an adaptor, and a pair of gripping jaws. The two-finger gripper with linear stroke is an off-the-shelf product. For standard batt insulation, its width is larger than the width of the cavity to achieve a tight-fit once inserted. These dimensional differences require the robot arm to apply compressive force to insert the batt insulation into the cavity. Therefore, a force-torque sensor that allows control of the applied force is mounted atop of the two-finger gripper. The gripping jaw adaptors are designed to connect the off-the-shelf gripper to the gripping jaws. The adaptors are CNC-machined L-shaped steel braces. The last component of the end-effector is the custom-built gripping jaws. The surface inside the jaw is textured to increase friction, with all else being equal reduces the grasping force, between the jaw and the insulation. The sizing of the jaw should be determined considering the dimensions and weight of the insulation, as well as its degree of elasticity. The jaw dimension is crucial to minimize the permanent deformation during manipulation.

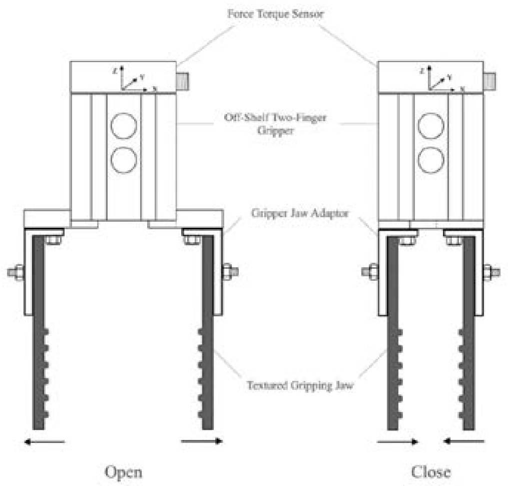

Figure 1. The proposed robotic end-effector.

3.3 Robotic Insertion Process Design

The proposed process for inserting batt insulation in this section is inspired by both the manual insertion process and the research conducted by Kim & Seo (2019). The research focused on the insertion of rigid objects into shallow cavities, incorporating primitive operations such as grasping, tilting, and tucking. In the context of batt insulation insertion, the proposed robotic insertion process, coined as GLITPP, contains six major steps: (1) Grasp, (2) Lift, (3) Insert, (4) Tilt, (5) Push, and (6) Press (as illustrated in Figure 2).

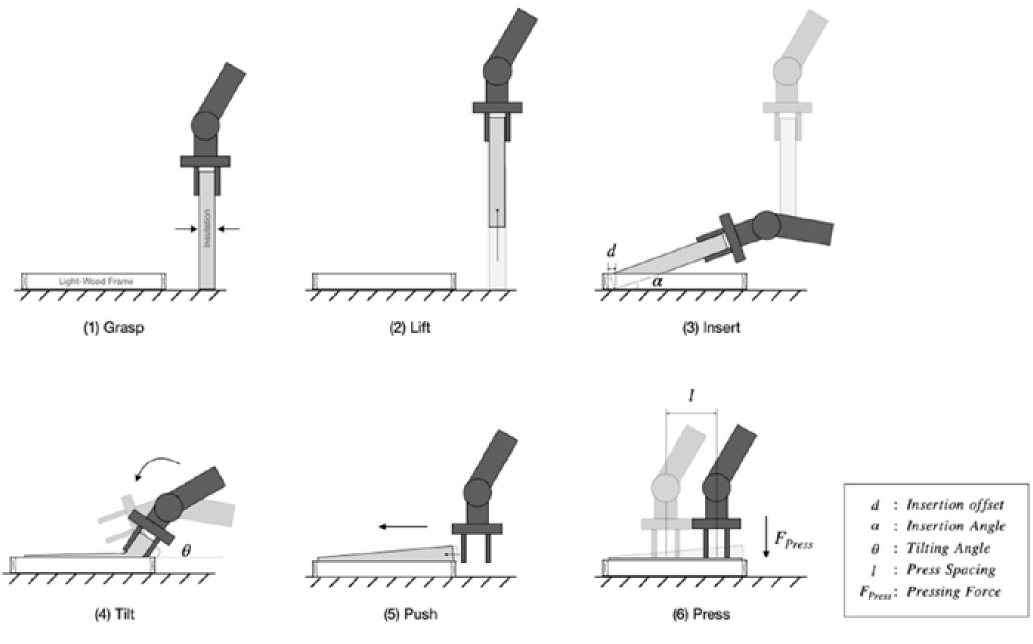

Figure 2. The GLITPP insertion process.

The initial step is to grasp the insulation from an initialized position. The robot arm moves to the top of the insulation using a point-to-point motion (PTP motion). Subsequently, the robot arm descends linearly (LIN motion) until the gripper reaches the insulation's top edge. Upon reaching the edge, the gripper closes to securely grasp the insulation. The second step is lifting. After grasping the insulation, a LIN motion is utilized to lift the insulation linearly. This is followed by a PTP motion to position the insulation in proximity of the frame cavity. In the third step, a combination of PTP and LIN motions is programmed to insert one edge of the insulation into the frame cavity with consideration of an insertion angle (α) and offset (d). For the fourth step, the end-effector is tilted. This ensures that when the grippers open, they avoid collisions with the frame and release the insulation without shearing it. Achieving this involves a PTP motion, tilting the end-effector to a specific angle (θ), and then releasing the insulation. To align the insulation accurately with the frame, pushing operations are employed along the uninserted edges. The robot arm utilizes LIN motions to enable the gripping jaws to gently push the insulation until it aligns flush with the cavity. For the final step, the gripping jaws are employed to press the uninserted edges of the insulation into the frame cavity, using defined press spacing (l) and pressing force (F_{Press}) parameters. The pressing pattern initiates from the corners of the inserted edge and proceeds along the edges perpendicular to the inserted edge and then finally along the parallel uninserted edge. The task description and associated robot motions outlined above are summarized in Table 1.

Table 1. Six steps of the GLITPP insertion process.

Steps	Task Description	Related robot motions
Grasp	From the initial position, the insulation is securely grasped by robotic gripper for pick up and manipulating.	1. PTP motion to the top of the insulation. 2. LIN motion down till the gripper reaches the insulation's edge. 3. Close the gripper.
Lift	The robot arm picks up the insulation and moves it close to the frame cavity.	1. LIN motion to lift the insulation. 2. PTP motion to move the insulation close the frame cavity.
Insert	The robot arm inserts the insulation into the cavity with an insertion angle (α) and offset (d).	1. PTP motion to rotate the insulation. 2. LIN motion to insert the insulation into the cavity.
Tilt	The robot arm tilts the insulation to a tilting angle (θ).	1. PTP motion to tilt the insulation
Push	The robot arm uses its gripping jaw to push the insulation along the uninserted edges of the insulation until it is flushed with the cavity.	1. LIN motion down till tip of the gripping jaw reaches the bottom of the insulation. 2. LIN motions parallel to the frame's direction to push the insulation into the cavity.
Press	The robot arm uses its gripping jaws to press the insulation into the frame cavity.	1. PTP motion to the pressing location. 2. LIN motions descend till the force reaches the pressing force. 3. LIN motion up. 4. LIN motion to the section pressing location 5. Repeat step 2 to 4 until the insulation is inserted.

4. IMPLEMENTATION & PARAMETER INDETIFICATIONS

4.1 Prototype of the End-effector

For the implementation, this research developed a prototype of the robotic end-effector (Figure 3). Detailed specifications of the end-effector components are listed in Table 2. The Robotiq FT 300-S Force Torque sensor, capable of measuring forces up to ±300 N and offering a data output of 100 Hz was utilized. Additionally, the Robotiq Hand-e gripper, with a maximum stroke length of 2 inches, was selected to serve as the parallel gripper. The custom adaptor was designed, in accordance with the Hand-e gripper specifications, to incorporate M3 screws for attachment onto the gripper's tracks. The gripping jaws, with dimensions of 4 inches by 4.5 inches and a thickness of 3/16 inch, were 3D printed with a textured interior surface at the lower section. The final assembly of the end-effector provides a clearance of 3.75 inches when the gripper is open and reduces to 1.75 inches when closed.

Figure 3. The prototyped robotic end-effector at Fully open position (left) and at fully closed position (right).

Table 2. Specifications for the prototyped end-effector.

Part	Manufacturer	Model	Specifications
Force torque sensor	Robotiq	FT 300-S	• Measuring range: ±300 N • Data output rate:100 Hz
Two-finger gripper	Robotiq	Hand-e	• Stroke: 2 in • Form-fit grip payload: 11 lbs • Friction grip payload: 8.8 lbs • Weight: 2 lbs • Gripping force: 20 to 185N
Adaptor	Custom-built	-	• Material: CNC machined steel
Gripping jaws	Custom-built	-	• Material: 3D printed PLA • Size: 4-inch (W) × 4.5-inch (L) × 3/16-inch (T)

4.2 In-lab Robotic Cell Setup

The in-lab robotic cell setup is illustrated in Figure 4. A Universal Robot UR5e was utilized as the robotic manipulator. The UR5e is a robot arm with 6 degree-of-freedoms. Its operational capacity is 11 lbs for payloads and accompanied by a maximum reach span of 33.5 inches. The robot arm was mounted on 46 inches by 34 inches table platform. The platform's upper surface is constructed from plastic, providing a smooth texture that minimizes friction effects between the insulation and the surface. Ultimately, the prototyped end-effector was affixed to the 6th axis of UR5e.

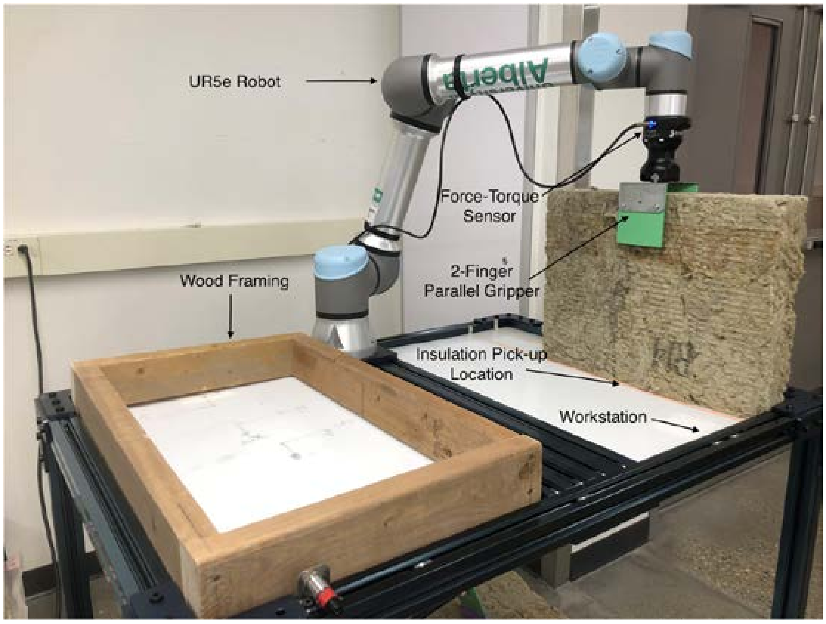

Figure 4. The in-lab robotic cell setup.

The light-frame wood wall utilized in this research is constructed using four 2 inches by 4 inches SPF Dimensional Lumbers. This lumber dimension is representative of a common type of light-frame wood wall used in building construction. The spacing between wood studs is set at 16 inches on-center, a standard stud spacing commonly employed in building construction, which results in a cavity width of 14.5 inches. Due to hardware constraints, specifically the reach of the robotic arm, the height of the wall cavity has been scaled to 26 inches, instead of the typical 8-foot wall. The overall dimensions of the wood cavity are 14.5 inches in width, 26 inches in height, and 3.5 inches in depth.

4.3 Parameters Identification

The GLITPP insertion process involves five key parameters: insertion angle (α), insertion offset (d), tilt angle (θ), press spacing (l) and pressing force (F_{Press}). These parameter values are determined through a series of individual robotic trials. All the trials are tested on 26 inches of mineral wool insulation. Once a set of feasible parameter values are ascertained, they are integrated to illustrate and formalize the entire robotic insertion process, the results of which will be presented in Section 5.

4.3.1 Insertion angle & Insertion offset & Tilt angle

There exists an interdependency among the insertion angle (α), insertion offset (d), and tilt angle (θ). Changes in the values of one parameter affect the other, as demonstrated by Eq.1. This equation represents an affine function that defines all points (x, y) on the outer surface of the fully opened gripper jaw in its tilted position. Notably, the parameter values must satisfy the condition that the affine function (hyperplane) is positioned to the left of the boundary point (P). This arrangement ensures collisions-free between the frame and the gripper. Figure 5 illustrates the variables used in Eq.1: L represents the distance from the tool center point (TCP) to the end of the insulation, H is the wood stud width, which is equal to the insulation thickness, W denotes the frame cavity width, E stands for the distance from the TCP to end of the gripper, G represents the distance between the center line and the outer surface of the gripper jaw in its fully open position, and P corresponds to the inner edge of the wood stud, serving as the boundary point.

$$y = (2x * \sin(\theta) - 2L * \sin(\theta - \alpha) + H * \cos(\theta - \alpha) - 2 * d * \sin(\theta) - 2G)/(2\cos(\theta)) \quad (1)$$

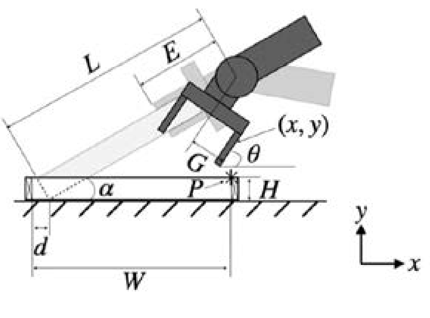

Figure 5. Illustration of the variables in Eq.1.

Due to the texturing on the gripper, a tilt operation is employed to facilitate the release of insulation from the gripper jaws after insertion into the frame cavity. This approach reduces disruptions to the insulation's intended position, prevents damage to its fibers by eliminating shearing, and allows for maintaining a minimal insertion angle. Thus, obtaining the minimum tilt angle is essential for achieving the effective release of insulation. The determination of this minimum tilt angle then allows for the calculation of the insertion angle and offset. Moreover, tilting indirectly contributes to the insertion process by pressing more edges of the insulation into the frame cavity. The minimum tilt angle is determined to be 55°, factoring in the insulation's weight and frictional forces. A list of trialed tilt angles and their corresponding outcomes are presented in Table 3.

Table 3. A list of trialed tilt angles with success rate.

θ (°)	Success Rate	Failure Mode
30	0/5	Insulations were pulled out of the frame cavity.
45	0/5	Insulations were first pulled, followed by shearing of the insulation fibers.
55	5/5	N/A

The insertion offset is the distance between the insulation and the frame's edge. When the offset is either too small or too large, the risk of collision increases during the insertion or pressing steps, respectively. This necessitates finding a balance between within the feasible range of offsets. Regarding the insertion angle, a smaller angle results in a longer edge of the insulation being inserted into the frame cavity. This minimizes the likelihood for the insulation edges to catch or snag during the subsequent titling and pressing steps, thus, ensuring proper seating of the insulation within the frame cavity. The lower limit of the insertion angle depends on the tilt angle in order to prevent collisions after titling when the grippers open to release the insulation. The insertion angle for a specific insertion offset, utilizing the minimum tilt angle obtained earlier, can be determined from Figure 6. This figure is generated by computing the solution pairs that satisfy Eq.1. Three combinations were selected for testing and the results are presented in Table 4. The tested minimum feasible combination of insertion angle and insertion offset is achieved at 30° with an offset of 0.75 inches.

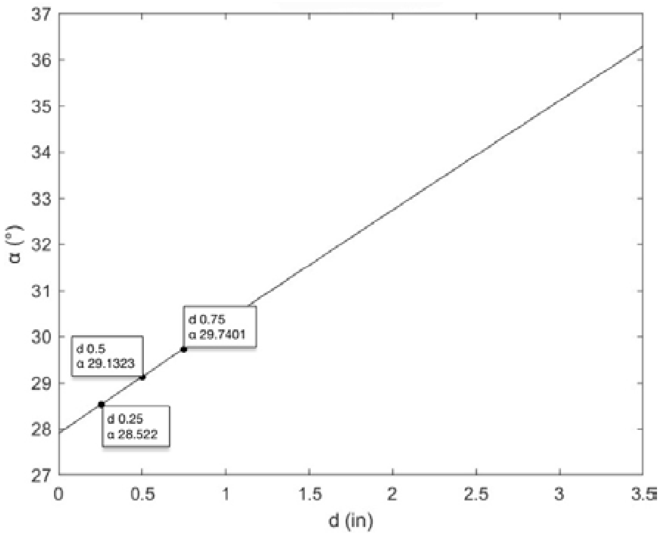

Figure 6. Combination of insertion angle and insertion offset.

Table 4. A list of trialed combination of insertion angle and insertion offset with success rate.

α (°)	d (in)	Success Rate	Failure Mode
29	0.25	0/5	Collision warning during insertion due to excessive compression of insulation.
29.5	0.5	0/5	Collision warning during insertion due to excessive compression of insulation.
30	0.75	5/5	N/A

4.3.2 Press spacing

The press spacing signifies the positions where the gripper will apply pressure along the uninserted edge of the insulation, facilitating its complete insertion into the frame cavity while ensuring no insulation edges remain exposed. While there are no explicit limitations on the quantity of presses, minimizing press count contributes to time efficiency. In the conducted trials, the center-to-center distance of the press spacing varies from 15 inches to 5 inches, with the initial press initiated from a corner. The outcomes of the trials are compiled in Table 5. It was noted that a 5-inch press spacing effectively accomplishes the insulation's insertion into the frame cavity, without any conspicuous convexity.

Table 5. A list of trialed press spacing with success rate.

l (in)	Success Rate	Failure Mode
15	0/5	Evident convexity noticeable between each press point.
10	3/5	Evident convexity noticeable between certain press points.
5	5/5	N/A

4.3.3 Pressing force

Once the press spacing is determined, it becomes crucial to apply the minimum amount of force necessary to press the insulation into the frame cavity. This approach ensures that the insulation avoids permanent deformation, which could lead to a loss of effective R-value. The lower and upper bounds for the pressing force are 80N and 120N, respectively. The results of the trials are listed in Table 6. It was determined that a pressing force of 100N fully and reliably presses the insulation into the frame cavity each time.

Table 6. A list of trialed pressing force with success rate.

F_{Press} (N)	Success Rate	Failure Mode
80	2/5	There were instances that the insulation was not fully pressed in.
100	5/5	N/A
120	4/5	There was an instance where the insulation had permanent deformation.

5. VALIDATION

The designed GLITPP insertion process, using the parameters obtained above as shown in Table 7, was tested with mineral wool and fiberglass batt insulations in two distinct scenarios that represent the actual configurations of insulation installation in construction: (1) a single piece of insulation filing the entire frame cavity, and (2) two pieces of insulation planed in tandem within the frame cavity. In Scenario 2, the process involved two steps: first inserting the 20-inch piece and then 6-inch piece to fill the entire frame cavity. During the insertion of the 6-inch piece, an additional 1-inch offset was applied between the two insulations to avoid the interaction of large frictional forces between the mating surfaces. For Scenario 1, ten tests were conducted for each insulation type. For Scenario 2, ten tests were conducted for each step and each insulation type. Each test was performed using new insulation to simulate the actual application in construction.

Table 7. Summarized selected parameter values obtained from Section 4.3.

Parameter	Value
Tilt Angle (θ)	55°
Insertion Angle (α)	30°
Insertion Offset (d)	0.75 in
Press Spacing (l)	5 in
Pressing Force (F_{Press})	100 N

5.1 Results and Discussion

Table 8 summarizes the experiment results using the selected parameters obtained in Section 4.3. Fig. 8 shows the progress of all the experiments and final insertion completion with the front and back of the insulation. The success of the entire GLITPP insertion process is defined by the insulation fitting tightly within the frame cavity, the absence of visible voids and gaps between the insulation and wood frame, and the insulation having no shearing or permanent deformation. The overall success rate stands at 93.3%.

Table 8. Experiment results for entire GLITPP insertion process.

Scenario	Insulation Length (in)	Batt Insulation Type	Success Rate
1	26	Mineral Wool	9/10
1	26	Fiberglass	10/10
2.1	20	Mineral Wool	10/10
2.1	20	Fiberglass	9/10
2.2	6	Mineral Wool	8/10
2.2	6	Fiberglass	10/10

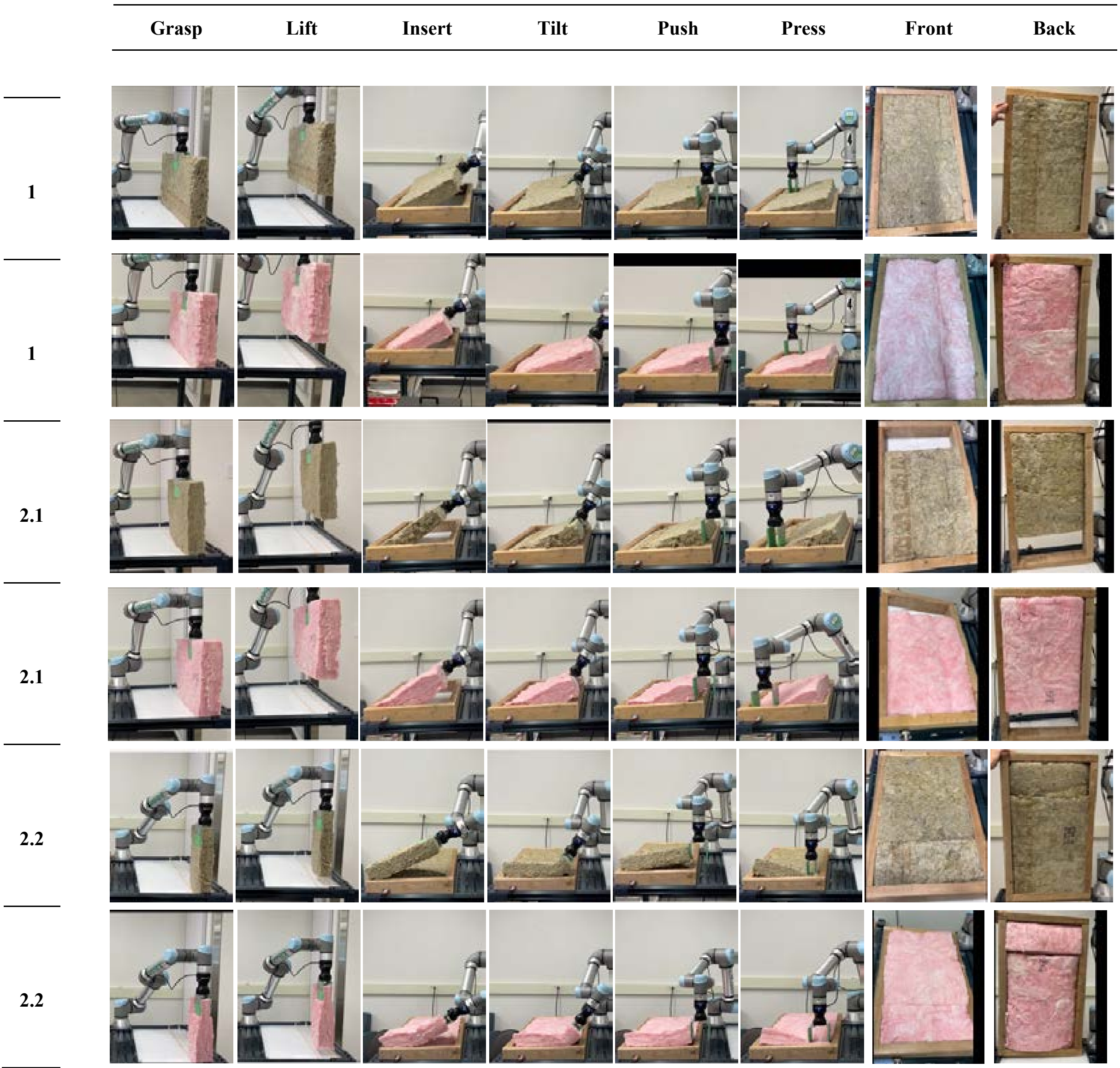

Figure 8. Experiment progress. Each row is the scenario associated with the corresponding rows of the Table 7.

The high success rates, as showed in Table 8, were achieved by mitigating the negative effects of deformation and uncertainties in mechanical properties through the GLITPP insertion process. The integration of individual parameter identification into a single continuous process, facilitated by custom-built grippers, is seamless and repeatable. The results substantiate that the manipulation of deformable insulation using the designed grasping, lifting, and inserting steps yields high accuracy in achieving target positions. The tilting step reduces the risk of shearing of the insulation during release, while the pushing step offers guidance that minimizes uncertainties and random disturbances before pressing. Ultimately, the pressing step ensures a tight-fitted insulation within the frame cavity, without any discernible gaps and deficiencies. A notable feature of the GLITPP process is that it can be extended to full-scaled 2x4 light-frame wood wall panels and light-frame wood wall panels with varying wood stud sizes, achieved by employing different sizes/numbers of grippers and tuning of parameters.

There were four instances in which the GLITPP process did not succeed. In scenario 2.1, the failure was an outlier, as no defects were observed in the insulation. For scenarios 1 and 2.2, the lack of success resulted from pre-existing creases and pockets of low-density in the insulation. Notably, the insulations used in validation were all chosen randomly from the packaging without any rejection of unideal pieces of insulation. Incorporating insulation pre-inspection, selection, and rejection would raise the success rate.

6. CONCLUSION

This research introduces a robotic method to insert batt thermal insulation into light-frame wood wall frame. The method comprises two major components: a custom-built end-effector and a corresponding robotic insertion process. The design of the robotic end-effector integrates seamlessly with an off-the-shelf two-finger gripper. The end-effector is constructed of a force-torque sensor, a two-finger gripper, an adaptor, and a pair of gripping jaws. The proposed robotic insertion process, named GLITPP, encompasses a sequence of six major steps: Grasp, Lift, Insert, Tilt, Push, and Press. To identify the variable parameters within the GLITPP insertion process, an in-lab robotic cell equipped with a prototyped end-effector was utilized. Through a series of individual robotic trials and iterative refinements, these parameter values were determined. The effectiveness and feasibility of the proposed robotic method were evaluated using two common batt thermal insulations: mineral wool and fiberglass. Test scenarios encompassed both a single insulation piece filling the entire frame cavity and the tandem placement of two insulation pieces within the cavity. The results exhibited a remarkable 93.3% success rate for the GLITPP insertion process. To ensure the broader applicability of the proposed method, future works will involve testing the GLITPP insertion process on a larger capacity robot arm with full-scaled panels. Additionally, the integration of an insulation condition identifying sensor is envisioned, enhancing adaptability by combining it with our robotic insertion process.

7. ACKNOWLEDGEMENTS

This research was financially supported by Mitacs under Design of Prefabricated Exterior Wall Panels for Robotic Building Retrofit Project ID IT32540, NSERC ALLRP under Practical Methods for Efficient Estimation of Effective Thermal Resistance of Exterior Walls Project ID 566879-21, and Tecnologico de Monterrey under Seed Grant Program Robotic Wall Construction Using Innovative Building Bl and Challenge-Based Research Funding Program 2022 project ID IJXT070-22TE6000.

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THE IMPACTS OF DIGITAL FABRICATION ON THE CONSTRUCTION INDUSTRY: A SYSTEMATIC REVIEW

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ABSTRACT: *The building industry is a major consumer of natural resources and a large contributor to environmental degradation, leading to a need to rethink current building practices. Digital fabrication (Dfab) technologies, which transform design and engineering data into physical products, are gaining traction in the Architecture, Engineering and Construction (AEC) industry. This study aimed to evaluate the implications of digital fabrication in the construction industry, by identifying the current Dfab applications and the hindrances that are limiting its implementation. The research questions addressed were why Dfab is essential in the construction sector, the current state-of-the-art of Dfab in the construction industry, and how Dfab is improving the construction industry. Through a systematic literature review, the findings proposed that Dfab can revolutionize the construction sector, enabling freeform architecture, reducing construction costs, cutting material waste, and increasing worker safety. Nevertheless, further research is needed to overcome obstacles such as high costs and the lack of digital skills in the construction industry.*

KEYWORDS: *Digital fabrication, Construction industry, Project management, Digital technology, Systematic review.*

1. INTRODUCTION

The building industry is recognized as a large consumer of natural resources and a significant contributor to environmental impacts and is considered an inefficient manufacturing process (Wu, Wang and Wang, 2016). It is still working to improve the situation and boost overall productivity, but there are obstacles to overcome (García de Soto *et al.,* 2018). To address environmental challenges, there is a need to rethink conventional building models and techniques due to the predicted increase in global population in the coming decades (Naboni, Breseghello and Kaunic, 2019). To promote sustainability, the architectural profession needs to develop fully automated production forms and processes (Tuvayanond and Prasittisopin, 2023).

The ability to create objects directly from design information is causing a transformation in many fields of design and production (Agustí-Juan and Habert, 2017). The key to fostering high-quality industry growth is creating and applying digital transformation (Yuan *et al.,* 2022). The use of digital fabrication (Dfab) technologies is rapidly increasing in the Architecture, Engineering and Construction (AEC) industry (Graser, Kahlert and Hall, 2021). The "third industrial revolution," also known as digital fabrication, is anticipated to revolutionize the construction sector by allowing freeform architecture, lowering construction costs, reducing material waste, and raising worker safety (Wangler *et al.,* 2016). Dfab refers to a construction process that utilizes digital code to control manufacturing devices and processes, allowing for the seamless conversion of design and engineering data into physical products (Graser, Kahlert and Hall, 2021). Dfab is an automated fabrication method that uses data to enhance efficiency and productivity (Ng and Hall, 2021).The technology began developing more than 25 years ago, but its rapid development started later (Žujović *et al.,* 2022). The use of Digital design and fabrication technologies have created methods and processes for producing more complex and customised architectural solutions while still utilising standard building materials over the last two decades (Carvalho and Sousa, 2014). Integrating design and construction is essential for new technologies such as digital fabrication, and a specialised design management strategy is required to overcome integration barriers (Ng, Graser and Hall, 2023). Digital technology allows for better control, increased construction efficiency, the removal of the need for conventional formwork, and the ability to customise building materials during the construction process compared to traditional methods (Yuan *et al.,* 2022). The use of computational design and robotic fabrication together has the potential to bring about significant advancements in the form and structure of architecture (Agustí-Juan and Habert, 2017).

Digital fabrication necessitates a redesign of the design process. Thus, there is a need for a better understanding of digital systems in areas such as technical development, technological systems, organisational contexts, contractual provisions, and business models (Ng *et al.,* 2022). However, the use of additive Dfab in large-scale construction is still in its early stages and requires overcoming challenges in changing traditional construction processes and roles of those involved in the project (García de Soto *et al.,* 2018).

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Mehdi Keshtkar, Emmanuel Daniel, Louis Gyoh, *The Impacts of Digital Fabrication on the Construction Industry: A Systematic Review,* pp. 605-615,

A BIM platform is not essential for Dfab design in small-scale projects, as long as there is integration of process, information, and organisation (Ng, Graser and Hall, 2023). BIM is a cutting-edge digital system that promotes innovation and enhances project values through information integration in construction projects, which also involves changes in design management and overall best practices (Ng, Graser and Hall, 2023). Different non-destructive methodologies to capture complex shapes have been developed through the use of photographs, video-recording, laser sensors and LED light projections, demonstrating the significant advantages in speed and accuracy that these digital methods can offer compared to conventional analogue processes (Lorenzo and Mimendi, 2020). Many countries have plans to increase the proportion of construction activities carried out off-site (Kim, Cuong and Shim, 2022). However, the effectiveness of DFAB is determined by the inclusion of fabrication information and organization in the design process, which can be challenging to achieve in traditional delivery models such as Design-Bid-Build (Ng and Hall, 2021).

Project management and delivery models have shifted fundamentally due to the digitization of project information (Hall, Whyte and Lessing, 2020). The uniqueness of each construction work is due to its immobility, customization of both construction works and processes, and interdisciplinarity (Bischof, Mata-Falcón and Kaufmann, 2022). DFAB techniques combine automated subtractive, formative, or additive building methods with computational design approaches (García de Soto *et al.,* 2018). An alternative to costly and inefficient manufacturing practices was proposed through automation in construction and architecture (Tuvayanond and Prasittisopin, 2023). The limits of architectural design and production may be expanded by digital fabrication techniques (Agustí-Juan and Habert, 2017). Dfab adoption faces not only technical challenges, but also organizational and process barriers, as it involves multiple research disciplines and professions such as architects, materials scientists, roboticists, structural engineers, manufacturers, and trade contractors (Graser, Kahlert and Hall, 2021). However, there is a desire to investigate alternative methods of creating formworks using digital fabrication technology (Carvalho and Sousa, 2014).

In recent years, the intersection between digital fabrication techniques and cementitious materials has become significant (Wangler *et al.,* 2016). Digital fabrication with concrete is a newly developed and wide-ranging field that can potentially reduce environmental impact and promote industrialization in construction while meeting various construction requirements (Bischof, Mata-Falcón, & Kaufmann, 2022). Modern product creation has shifted to rely heavily on 3D printing (Agustí-Juan & Habert, 2017). Digital fabrication has been applied to the production of formworks using concrete, a significant application of this technology (Wangler *et al.,* 2016). However, in free-form, digital fabrication using concrete, accurately predicting the material's mechanical properties in its fresh state is crucial to ensure control over element deformations and overall stability during the printing process (Esposito *et al.,* 2021). Bucklin et al. (2023) describe a new construction method called the Mono-Material Wood Wall (MMWW), which employs subtractive manufacturing with digital control to enhance the functionality of wood and eliminate the need for other materials, thereby improving sustainability compared to traditional construction techniques. The impact of the fast-growing demand and regeneration rate of renewable building materials on the environment in the long term is yet to be determined despite the industry's shift towards them (Bitting *et al.,* 2022). However, using non-traditional renewable materials and developing suitable design and construction processes will be necessary for large-scale construction (Lorenzo & Mimendi, 2020).

According to Graser, Kahlert, & Hall (2021), it is crucial to reduce the time it takes to introduce new Dfab technologies to the market to speed up adoption, but this has been challenging. To successfully implement digital fabrication in the construction industry, better integration of fabrication-related information and organization into the design process is needed despite its growing emergence (Ng & Hall, 2021). Correspondingly, an increasing number of studies investigate the industry needs and strategies for adopting digital fabrication (Ng *et al.,* 2022). It is essential to research the environmental advantages of digital fabrication in architecture and construction, as it is still a developing technology, to make necessary adjustments in the early stages (Agustí-Juan and Habert, 2017). Despite extensive literature outlining its challenges, limited attention has been given to strategies employed in projects to successfully implement Dfab. The construction industry is currently focusing its research efforts on robotic fabrication, collaborative work between humans and robots, and prefabricated technologies as part of smart construction (Yuan *et al.,* 2022).

Given this, the current study determines the impact of digital fabrication on the construction industry. The study seeks to answer the following research questions:

1. Why is digital fabrication important in construction industry?
2. What is the state-of-the-art of digital fabrication related to construction industry?

3. How is digital fabrication improving the construction industry?

2. RESEARCH DESIGN AND METHODOLOGY

The analysis performed in this study identified the main research themes and categorized them based on the impacts of digital fabrication (Dfab) in the construction industry. The results may benefit other researchers as they summarise recent advancements, patterns, and potential research and innovation opportunities in the AEC sector. Based on the selected research philosophy, this study adopts a qualitative research strategy with an inductive approach. In qualitative research papers, the methods section emphasizes transparency of the methods used, such as the reasons, processes, and individuals involved in their implementation, to provide a deeper understanding and facilitate discussion of how they may have affected material's mechanical properties (Busetto, Wick and Gumbinger, 2020).

This study used the systematic literature review (SLR) method, that minimizes bias by exhaustively searching relevant studies through a systematic, transparent, and reproducible process (Chung, Lee and Kim, 2021). This study utilized the keyword search method and the snowball method to gather relevant information. In order to gather more information and discover papers that may have been overlooked, the keyword search and the snowballing technique were combined. To initiate the development of this study, the primary task was to identify the relevant keyword for retrieving research articles from academic databases. The following summary provides an outline of the process involved in this stage.

Researchers utilized the Scopus database, benefiting from its advanced search features, including filters for authors, affiliations, publication years, and document types, facilitating the discovery of pertinent and up-to-date research in specific fields. In the initial search for relevant literature, researchers employed the keyword string "[digital AND fabrication AND construction AND industry]" and obtained 300 documents. Subsequently, they applied specific restrictions, including open access availability, subject area in engineering, English language, and exact keywords "Digital Fabrication" or "Construction Industry," resulting in the retrieval of 47 documents directly related to their research topic.

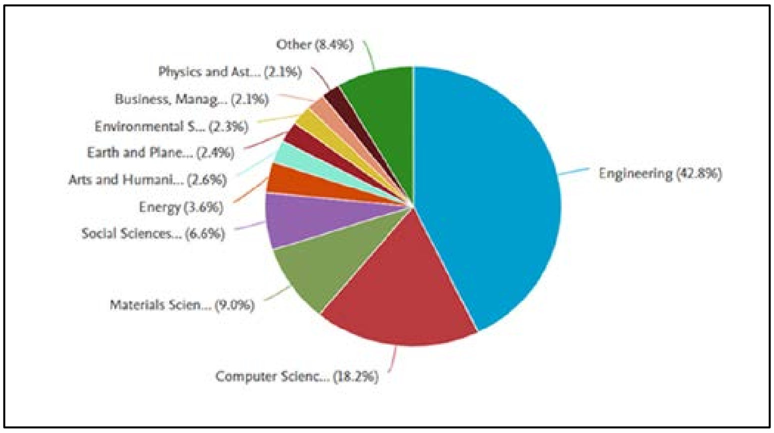

Figure 1: The distribution of documents by subject area before applying any restrictions to the search results in Scopus

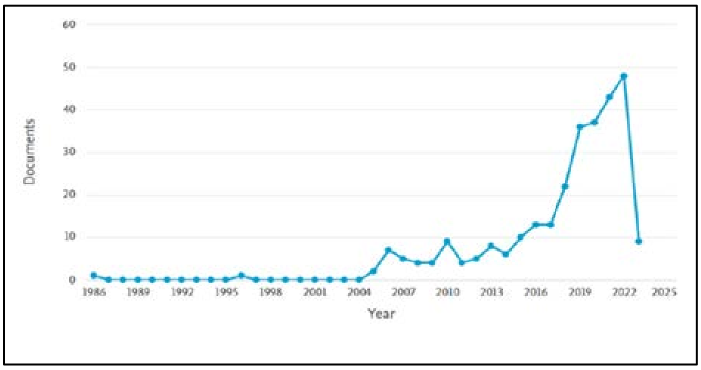

Figure 2: The distribution of documents by year before applying any restrictions to the search results in Scopus

The main objective of this section was to evaluate the appropriateness of the selected resources rather than the procedure itself. To determine eligibility, the study utilized an inclusion and exclusion approach, ensuring that only publications directly related to emerging digital fabrication in the construction industry were included. A benefit of these resources is that they contain highly relevant information pertaining to the study's topic. The researchers based their document selection on criteria that focused on the relevance of content to "Data Analysis and Management" in the most recent publications within the "Construction" field, specifically related to the use of "Digital Fabrication" in construction. Through an examination of titles, abstracts, and full texts, irrelevant documents were excluded, resulting in the selection of 27 articles that met these criteria.

The chosen resources were subject to content analysis, with most being journal articles providing comprehensive insights into digital fabrication in construction. While some sources were not directly construction-related, they still contributed to understanding the emerging digital technology. The selected studies utilized diverse qualitative or quantitative research methods, ensuring varied findings that enhance the credibility of this study concerning the research questions. Finally, the last step involved identifying the primary themes associated with the research questions.

3. DATA ANALYSIS AND MANAGEMENT

These documents' titles, abstracts, and full texts were examined to remove any irrelevant ones, resulting in 27 newly selected articles that are relevant to the study as shown in table1.

Table1: 27 newly selected articles that are relevant to the study

	Tittle	Year	Country	Source
1	Designing for Digital Fabrication: An Empirical Study of Industry Needs, Perceived Benefits, and Strategies for Adoption	2021	Switzerland	Journal of Management in Engineering
2	DFAB HOUSE: implications of a building-scale demonstrator for adoption of digital fabrication in AEC	2021	Switzerland	Construction Management and Economics
3	Digital fabrication, BIM and early contractor involvement in design in construction projects: a comparative case study	2023	Switzerland	Architectural Engineering and Design Management
4	Environmental assessment of multi-functional building elements constructed with digital fabrication techniques	2019	Switzerland	The International Journal of Life Cycle Assessment
5	Feasibility study of large-scale mass customization 3D printing framework system with a case study on Nanjing Happy Valley East Gate	2022	China	Frontiers of Architectural Research
6	Mirror-breaking strategies to enable digital manufacturing in Silicon Valley construction firms: a comparative case study	2020	Switzerland	CONSTRUCTION MANAGEMENT AND ECONOMICS
7	Multi-scale design and fabrication of the Trabeculae Pavilion	2019	Denmark	Additive Manufacturing
8	Productivity of digital fabrication in construction: Cost and time analysis of a robotically built wall	2018	United Arab Emirates	Automation in Construction

9	Teaching Target Value Design for Digital Fabrication in an Online Game: Overview and Case Study	2021	Switzerland	29th Annual Conference of the International Group for Lean Construction
10	Design for Manufacture and Assembly of Digital Fabrication and Additive Manufacturing in Construction: A Review	2023	Thailand	Buildings
11	3D Printing Technologies in Architectural Design and Construction: A Systematic Literature Review	2022	Serbia	Buildings
12	Challenges and Opportunities in Scaling up Architectural Applications of Mycelium-Based Materials with Digital Fabrication	2022	Switzerland	Biomimetics
13	A critical review of the use of 3-D printing in the construction industry	2016	Australia	Automation in Construction
14	Digital Concrete: Opportunities and Challenges	2016	Switzerland	RILEM Technical Letters
15	Digital Fabrication Technology in Concrete Architecture	2014	Portugal	32nd International Conference on Education and research in Computer Aided Architectural Design in Europe
16	Digital Fabrication for DfMA of a Prefabricated Bridge Pier	2022	South Korea	The 17th East Asia-Pacific Conference on Structural Engineering & Construction
17	Digitisation of bamboo culms for structural applications	2020	United Kingdom	Journal of Building Engineering
18	Early-age creep behaviour of 3D printable mortars: Experimental characterisation and analytical modelling	2021	Italy	Materials and Structures
19	Environmental design guidelines for digital fabrication	2017	Switzerland	Journal of Cleaner Production
20	Environmental Impact of a Mono-Material Timber Building Envelope with Enhanced Energy Performance	2017	Germany	Sustainability
21	Fostering innovative and sustainable mass-market construction using digital fabrication with concrete	2022	Switzerland	Cement and Concrete Research
22	Framework for technical specifications of 3D concrete printers	2021	South Korea	Automation in Construction
23	Identifying enablers and relational ontology networks in design for digital fabrication	2022	Switzerland	Automation in Construction
24	Rethinking reinforcement for digital fabrication with concrete	2018	Italy	Cement and Concrete Research
25	Toward Lean Management for Digital Fabrication: a Review of the Shared Practices of Lean, DfMA and dfab	2019	Switzerland	27th Annual Conference of the International Group for Lean Construction (IGLC)
26	Towards Automated Installation of Reinforcement Using Industrial Robots	2019	Sweden	2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)
27	Using Computer Vision for Monitoring the Quality of 3D-Printed Concrete Structures	2022	India	Sustainability

Figure 3 displays the distribution of chosen documents based on their year of publication, while Figure 4 illustrates the distribution of chosen documents based on the country where the research was conducted.

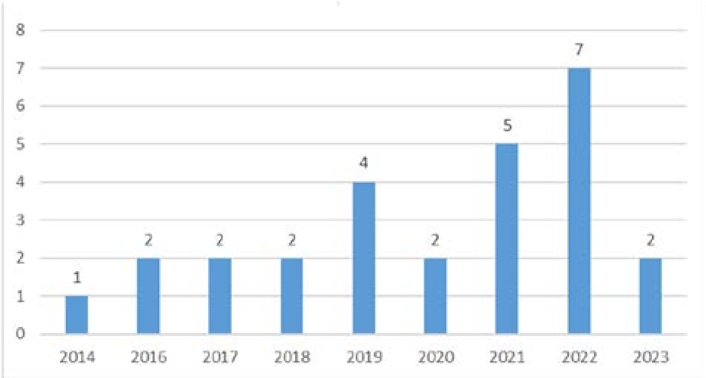

Figure 3: The distribution of chosen documents based on their year of publication

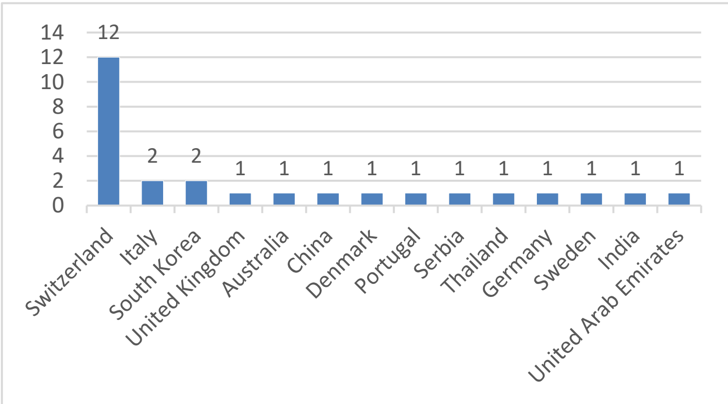

Figure 4: The distribution of chosen documents based on the country where the research was conducted

4. RESULT AND DISCUSSIONS

4.1 Qualitative Analysis and Discussion

The study aim to present an overview of the impacts of digital fabrication in the construction industry.

4.1.1 Importance of digital fabrication in the construction industry

Due to industry fragmentation, the AEC sector adopts new technologies more slowly than other sectors, but the emergence of Digital Fabrication (DFAB) offers a systematic innovation that can help with this problem (Ng, Graser and Hall, 2023). Recent studies have focused on the impact of new digital technologies like Building Information Modelling (BIM) on design management (Ng, Graser and Hall, 2023). Although a complete consolidation that outlines the factors contributing to the design process for digital fabrication is currently unavailable (Ng *et al.,* 2022). However, research on Dfab is still in its early stages. It lacks well-developed mechanisms allowing full-scale project adoption in the sector (Ng and Hall, 2019).

According to Ng et al. (2022), igital Fabrication is becoming increasingly common due to its potential to improve project efficiency by connecting design and construction processes, and it can be categorized into five groups: technological systems, organizational framework, contractual terms, and business models. Two possible approaches for dfab management are provided by lean construction management and design for manufacture and assembly (DfMA) (Ng and Hall, 2019). Adopting DFAB has many advantages, such as increased productivity and resource efficiency, reduced waste in the building industry, and increased worker safety (Graser, Kahlert and Hall, 2021).

Projects offer a distinct opportunity to investigate and add to the emerging understanding of Dfab in AEC due to their capacity to integrate complex knowledge (Graser, Kahlert and Hall, 2021). The adoption of Dfab in AEC faces significant challenges due to the industry's fragmentation, weak coordination between contractors, and high participant turnover between project phases, making the organizational and social context as important for industry adoption as technological feasibility (Graser, Kahlert and Hall, 2021). To minimize environmental impacts, structural complexity should result from material reduction strategies such as structural optimization or multi-functionality (Agustí-Juan, Jipa and Habert, 2019).

According to Agustí-Juan, Jipa and Habert (2019), Digital fabrication techniques that achieve multi-functionality lead to a construction process that is efficient in its use of materials and has significant environmental benefits during production. The on-site mass production of complex, customised structures is made possible by digital fabrication in building (Agustí-Juan and Habert, 2017). With the projected increase in global population, it is necessary to rethink traditional building methods and establish new techniques to reduce the environmental impact of the construction sector. Digital fabrication can aid in this effort by reducing material usage and overall environmental impact (Naboni, Breseghello and Kunic, 2019).

However, to make a positive change in the built environment, this mode of digital architecture is expected to work towards fully automated production forms and processes that promote equality, sustainability, democracy, diversity, and inclusiveness (Žujović *et al.,* 2022). Collaboration between structural engineers, roboticists, builders, and material scientists will be crucial for digitally fabricating concrete (Wangler *et al.,* 2016).

4.1.2 The state-of-the-art of Digital Fabrication related to the construction industry

Academic and industrial applications have explored various additive technologies in different scales and contexts, from thermoplastics to clay, gantry 3D printers to robotic arms and drones (Naboni, Breseghello and Kunic, 2019). Many researchers are looking into robotic 3D printing, a new digital fabrication technique, to address the problem of traditional building methods' declining productivity (Yuan *et al.,* 2022).

On-site digital fabrication, which aims to bring additive fabrication processes to construction sites, is divided into three main categories: large-scale robotic structures, mobile robotic arms, and flying robotic vehicles (García de Soto *et al.,* 2018). Scholarship explores the use of digital systems, such as BIM platforms that can help stakeholders coordinate the management data, including 3D models and algorithms that link to digital fabrication (Ng *et al.,* 2022).

The data from the researched case study by Graser, Kahlert and Hall (2021) indicates that implementing DFAB projects can increase its acceptance as a legitimate practice in AEC. However, for DFAB adoption to be successful, it needs to be accepted not just within the project organization but also outside it. Large-scale AM machines are being used to construct recent architectural projects globally, which has sparked a growing interest in implementing and expanding the technology within the construction industry and architecture (Tuvayanond and Prasittisopin, 2023). A study by Bitting et al. (2022) provides an overview of the current state of research and applications of mycelium-based materials, emphasizing digital fabrication, production, and design and discussing issues such as low mechanical properties and the absence of standardized production methods. The use of digital design information to drive production processes, such as 3D extrusion printing, CNC machines, and robotic assembly, is known as digital fabrication, and it is an essential component of modern construction processes (Ng *et al.,* 2022).

Wu, Wang and Wang (2016) explored the significance of component design about 3D printing capabilities and raw material performance and the potential benefits of using BIM to support design variations and improve performance, while also reducing the time and costs associated with design changes and reprinting.

Despite the potential advantages of automation, there have been few cases of robots being used to automate construction in recent years (Relefors *et al.,* 2019). The prefabricated bridge construction process has used DfMA, a design method commonly used in manufacturing manufacturing (Kim, Cuong and Shim, 2022). Digital fabrication techniques can be categorized into subtractive methods such as milling and cutting, and additive methods such as 3D printing, which has become increasingly popular and accessible for home use (Agustí-Juan and Habert, 2017).

Bischof, Mata-Falcón and Kaufmann (2022) assert that widespread adoption of digital fabrication in the construction industry is critical to making a meaningful impact on improving its environmental impact, but currently, it has not yet reached the mass market. Chung, Lee and Kim (2021) point out that despite the rapid expansion of research and market for 3D concrete printing (3DCP), there is a lack of a widely accepted technical specification framework for comparing 3DCPs with various characteristics. Despite automation initiatives in both research and industry, such as Built Robotics and MX3D, the construction industry has not yet demonstrated a shift towards automation (Relefors *et al.,* 2019).

4.1.3 How Digital Fabrication improves the construction industry

Digital fabrication has the potential to bring about extensive positive impacts, such as improved material efficiency and waste avoidance, reuse of materials, workplace health and safety, integrative work design, and productivity (Graser, Kahlert and Hall, 2021). The integration of digital and manual tasks was crucial for the project, and there was a need for better collaboration processes with digital machinery (Graser, Kahlert and Hall, 2021). The productivity rate for robotic construction is constant, which means it doesn't depend on the complexity level of the construction (García de Soto *et al.,* 2018). Concrete 3D printing reduces waste production by 60%, construction time by 50-70%, and labour costs by 50-80%, potentially decreasing construction costs by up to 35% while improving the industry's sustainability (Senthilnathan and Raphael, 2022).

To promote sustainable development opportunities through the use of digital systems, design modeling with parametric modeling capacity can be utilized to minimize rework and waste by testing the feasibility and soundness of integrated digital twin models through physical mockups prior to tendering (Ng *et al.,* 2022). Despite being promoted in various countries, there is a lack of consistency and diversity in stakeholder perspectives and research advancements regarding the implementation of digital fabrication, with interdependencies between industry needs creating complexities for stakeholders to adopt such projects, further hindering their adoption on a larger scale, highlighting the need for a better understanding of industry practitioners' needs and how they are related to one another (Ng *et al.,* 2022).

According to the research by Ng and Hall (2021), Target Value Design (TVD) implementation can help manage and optimize DFAB processes to meet time, cost, profit, and aesthetic requirements in less time while maintaining the needs of stakeholders. The conventional Design-Bid-Build model's separate processes can impede the implementation of digital fabrication techniques by making it difficult for stakeholders to manage project costs (Ng and Hall, 2021). Digital fabrication is anticipated to result in a more sustainable construction industry by enabling more efficient structural design that uses materials only where necessary and by reducing waste generation through more efficient construction techniques, particularly about formwork (Wangler *et al.,* 2016).

5. RECOMMENDATIONS AND DIRECTIONS FOR FUTURE RESEARCH

The impacts of digital fabrication in the construction industry are still an area that requires further research. Several recommendations and directions for future research can be made based on the reviewed literature. One area that requires investigation is the potential economic benefits of digital fabrication in construction projects. Future studies could conduct a cost-benefit analysis to provide a clearer understanding of the potential economic benefits that could be achieved by implementing digital fabrication in the construction industry. Another area that requires exploration is the potential environmental benefits of digital fabrication in the construction industry. Future studies could focus on the potential environmental benefits that could be achieved through digital fabrication in the construction industry, such as reducing waste and carbon emissions. In addition, future research could investigate the best strategies for implementing digital fabrication in the construction industry. This could include examining the barriers to adoption, identifying practical training and education programs, and exploring the potential role of government policies and incentives. The reviewed studies provide valuable insights into the impacts of digital fabrication in the construction industry. They are applicable in various areas within the field, including but not limited to construction management, architecture, and engineering. For example, the studies provide insights into the potential benefits of digital fabrication in terms of cost, time, and quality management in construction projects. They also provide insights into the potential for digital fabrication to revolutionize the design and construction of buildings and other structures, as well as improve the efficiency and effectiveness of engineering processes in the construction industry.

One potential research question that could be addressed in future studies is: What are the best strategies for overcoming the barriers to adoption of digital fabrication in the construction industry? This question would be designed to address the identified need for research on implementation strategies and could help to provide insights into how digital fabrication can be successfully integrated into the construction industry.

6. CONCLUSION

The research on the impacts of digital fabrication in the construction industry highlights the potential benefits and challenges associated with adopting this technology. Through a systematic literature review, the study explores the current state of digital fabrication (Dfab) in construction, its significance, and its potential to improve the sector.

The study's extensive research has provided valuable insights into how digital fabrication could bring about a revolution in the construction sector. Firstly, Dfab enables the creation of intricate and customized structures that were previously impossible using conventional methods, thus offering new possibilities for innovative and sustainable designs that can shape the industry's future. Secondly, Dfab has the capacity to substantially lower construction costs and minimize material waste, thereby boosting efficiency and contributing to resource conservation, a crucial factor for environmental sustainability. Additionally, the adoption of Dfab could enhance worker safety by automating hazardous tasks and reducing the necessity for manual labor in risky conditions. Despite the intriguing benefits, the study has brought to light the difficulties that prevent Dfab from being widely used in the building industry. To effectively utilise the promise of digital fabrication, significant barriers such as high starting prices and a lack of digital expertise in the market must be overcome. Also, there are organisational and operational challenges when incorporating Dfab into conventional building processes and delivery models, which emphasises the necessity of communication and cooperation across many disciplines.

The qualitative analysis conducted in this study highlights the importance of seamless integration and collaboration among various stakeholders, such as architects, engineers, roboticists, and material scientists, for the successful deployment of Dfab technologies in the construction industry. Furthermore, the adoption of digital fabrication calls for a comprehensive redesign of the design process, considering technical development, organizational contexts, contractual provisions, and business models.

This study was limited to academic journals, articles, and conference proceedings found in the listed scientific sources. Following an inductive methodology that only used secondary data, the qualitative analysis and discussion were conducted. Primary data, however, might have provided a more in-depth and analytical grasp of the subject.

The study recommends further research to investigate the economic and environmental benefits of implementing Dfab in construction projects. Additionally, it emphasizes the need to identify effective strategies for overcoming barriers to adoption to ensure successful integration.

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EFFICIENT DATA CURATION USING ACTIVE LEARNING FOR A VIDEO-BASED FIRE DETECTION

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ABSTRACT: *Video-based fire detection is a crucial object detection problem that relies on accurate and reliable data to detect fires. However, collecting and labeling fire-related data can be time-consuming and expensive, making it difficult to obtain sufficient data for training machine learning models. To address this challenge, uncertainty-based active learning techniques can be used to iteratively select the most informative samples for labeling. This can reduce the amount of labeled data needed to achieve high model performance and has the potential to even prune the training data with fewer informative samples. The traditional sampling-based uncertainty estimation methods are computationally expensive. Hence, an efficient prior network-based ensemble distillation State-of-the-Art approach is evaluated on an internal dataset which still requires relatively higher overhead computation making it difficult for production deployment. A biased softmax differencing-based uncertainty approach and a feature-based hard data mining approach are proposed and compared with the distillation approach. The novel approaches are found to have a very low overhead uncertainty estimation time compared to the ensemble distillation approach and traditional sampling techniques. The methods are evaluated in the context of curating the unlabeled pool data and improving the training data. For completeness, the experiments are performed on three different data sizes, and overall, the frame-wise selection strategy is proved to be better than the sequence-wise querying strategy. The Principal Component Analysis (PCA)-based hard data mining outperformed other methods and improved the model performance by 16.33% with* $AUC_{2\%}$ *metric when compared with the random selection of data. The approach even outperformed the main network trained on full data by 7.33%, henceforth improving the training data by using informative 26.39% data. The results indicate that novel data mining provides efficient training and pool data curation.*

KEYWORDS: *Uncertainty Estimation, Active Learning, Object Detection, Outlier Detection, Feature-based cluster analysis, Video-based Fire Detection*

1. INTRODUCTION

Traditional smoke detectors require a volume of smoke to reach the detector location and hence generally have a high detection time. Thermal cameras (Sousa, et al. 2020) on the contrary are quite expensive and work in the infrared spectrum resulting in fire detection only when there is significant heat produced. There is no visual confirmation of the fire when using thermal cameras. Hence, deep learning-based video detection can be the solution to decrease the detection time and detect fires based on patterns in the video rather than heat produced. However, for an industrial Deep Learning (DL) application of Fire Detection (FD), the speed and the reliability of the predictions are of major concern. The non-reliability can lead to high economic losses and even human endangerment. Late detection can cause heavy economic and even human losses. Speaking about statistics in the industrial setting in the USA, 1.2 Billion $ in economic loss along with 16 deaths and 273 injuries occur annually (Campbell, 2018) indicating the importance of reliable video-based fire detection. However, in order to have a reliable DL model for detecting fire, the data selected for the model training should be of high quality.

The research takes inspiration from Peter Norvig's quote: "*More data beats clever algorithms, but better data beats more data*". The traditional thinking of improving a DL model by increasing the quantity of the data in object detection does not answer why the new data is being added to the training data. Nevertheless, even if large amounts of data is readily available, in object detection problem, the requirement of labeled data raises the cost of annotation massively. In order to improve the performance of the model and simultaneously decrease the cost of labeling, the most informative data have to be sampled.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Keyur Joshi, Angelina Aziz, Philip Dietrich, Markus König, *Efficient Data Curation Using Active Learning for a Video-Based Fire Detection*, pp. 616-624, DOI 10.36253/979-12-215-0289-3.60

The aim of decreasing the annotation costs can be achieved by answering two questions: which data has to be selected and why? The passive learning models which receive the data randomly or by humans do not consider the informativeness associated with the data. However, the information is associated with uncertainty related to the data. With the help of uncertain information linked with the data, using Active Learning (AL), the informative data can be sampled iteratively. Sampling informative data using AL requires the estimation of uncertainty. The uncertainty can be referred to as a negative reliability score while a higher uncertainty score means low reliability. The uncertainty can help increase the reliability of the DL models by sampling informative uncertain data from the large dataset, thereby using AL to decrease the cost of the annotation. The concept of AL can assist in the data selection process or autonomously select data, which can subsequently be reviewed and labeled by a human annotator for subsequent training sessions.

The major contributions of our work can be summarized as follows:

- We propose two different methods for estimating uncertainty. One of the methods focuses on estimating uncertainty using feature space and the other approach uses softmax differences for uncertainty estimation.
- We compare different methods based on the time required for uncertainty estimation and the performance when implemented in an iterative AL setting.
- We experimentally show that our novel approach is efficient w.r.t time for uncertainty estimation. The approach even outperforms the State-of-the-Art (SOTA) approach on the AUC metric in an active learning setting.
- We evaluate the performance of different methods w.r.t improving the full training data set by decreasing the data using AL.

2. RELATED WORK

Uncertainty estimation can be used as an additional component for the DL model to increase the trust and robustness of the SOTA architectures. DL models are often black box models, with often limited or no interpretability of the results. With the predictions of the DL model, uncertainty estimates can be incorporated to increase the reliability of the results from the black box models. Gal and Ghahramani (Gal & Ghahramani, 2016) introduced a Monte Carlo Dropout-based (MCD) uncertainty quantification method that has a very low overhead computation cost. The drop block-based uncertainty estimation (Deepshikha, *et al*. 2021) was proposed using Monte-Carlo DropBlock (MCDB). Deep ensembles (DeepEns) (Lakshminarayanan, *et al*. 2017) was used to estimate the predictive uncertainty using model re-training. The Test-Time-data Augmentation (TTA) (Manivannan, 2020) was compared with MCD, MCDB, and DeepEns in the context of uncertainty estimation. The research in the domain of uncertainty quantification is usually done in the fields of model and data uncertainty separately. However, one of the first methods combining the effects of both epistemic and aleatoric uncertainty was proposed in (Kendall & Gal, 2017). The loss function to estimate both uncertainties was suggested for the depth regression and segmentation tasks. Malinin and Gales proposed to estimate the predictive uncertainty of the deep learning model using Prior Networks (Malinin & Gales, 2018) which incorporated explicit modeling of distributional uncertainty. This approach parameterized the Dirichlet network over the categorical distribution to maintain the distribution extraction capability from the student model after the knowledge distillation (Malinin, *et al*. 2019). The Bosch internal research method of a low overhead FACER (Schorn & Gauerhof, 2020) based prior network (FacerDir) uncertainty quantification method will be used in the thesis as one of the SOTA methods for benchmarking. However, due to the high uncertainty estimation computation time, we propose novel approaches with both lower estimation time and more reliable uncertainty estimates.

With the need for better-performing object detection methods, the requirement of the data for training the SOTA architectures has also increased. In order to prioritize the labeling of the data and data curation, a lot of research has been done in the field of Active Learning. A comparison of various acquisition functions for computing uncertainty was done in the setup of AL (Nguyen, *et al*. 2022). Choi et al. (Choi, *et al*. 2021) proposed a probabilistic approach to estimate both the model and data uncertainty in a single pass and later performed Active Learning. The scalability and transferability were tested over the probabilistic Active Learning approach. An adaptive framework for active learning was developed and proposed in (Desai, *et al*. 2019) which performed adaptive switching between strong and weak supervision.

The present research in the fields of uncertainty estimation and AL will serve as the inspiration for the proposed paper, which aims to incorporate various techniques into the internal architecture of the Video-based Smoke Detection (VSD) model.

3. METHODOLOGY

An overview of the AL framework using different uncertainty estimation strategies using a business chart is depicted in Fig. 1. The chart illustrates the brief methodology of the approaches in an AL setting.

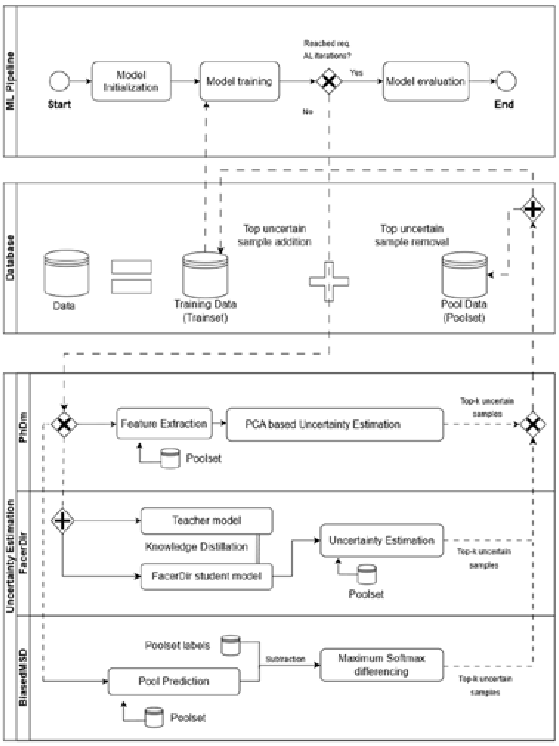

Fig. 1 Thesis methodology which describes the active learning framework implementation using various uncertainty estimation techniques.

3.1 Dataset

The dataset used in the thesis was developed by the engineering team at Bosch. As this dataset is a Bosch internal dataset, it is not available to the public. The dataset comprises Smoke and Non-smoke, “Negative” videos.

The dataset includes video sequences shot over 100 different locations. The locations can be classified into three major scenarios, viz. indoor, outdoor, and semi-outdoor. The scenarios which are shot in an indoor setting ranging from a parking lot to an industry are considered Indoor scenario. The outdoor scenario is a scenario shot in an open environment. The semi-outdoor scenario is on the contrary a setting in which there is a ceiling but lacks enclosure from all sides, resulting in a partially open space. Wind may be present in the outdoor setting and this changes the behavior of the smoke significantly.

3.2 Uncertainty Estimation

3.2.1 PCA-based Hard Data Mining (PhDm)

This approach is a novel method that is based on Principal Component Analysis (PCA) (Jolliffe & Cadima, 2016) for detecting hard samples from the pool data. PCA is a dimensionality reduction approach used to project the data to a low-dimension space and provide interpretability to the data. The PCA is applied to the feature vector space and reduced to the dimension of two. For every image sample, only the feature vector of the maximum prediction is used for dimensionality reduction as shown in Fig. 2.

The outliers found in the PCA plot were investigated and they were found to be often either hard or out-of-distribution examples. Hence, a density-based outlier detection method has been implemented to extract outliers from the PCA plot. Local Outlier Factor (LOF) (Breunig, *et al*. 2000) was used for detecting outliers in the plot which looks at the local density for each point. To query top outlier samples from the plot, a distance-based ranking is performed which ranks each outlier point based on the distance from the nearest inlier point.

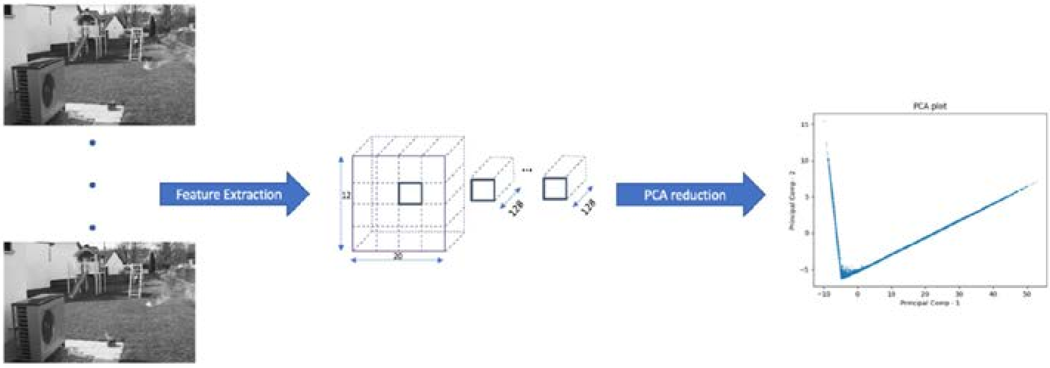

Fig. 2 Feature vector dimensionality reduction. The features (middle) are extracted through the model for the input images (left) and later PCA-based dimensionality reduction is performed. The bold patch represents the patch with maximum softmax prediction whose feature vector is used for dimensionality reduction.

3.2.2 Biased Maximum Softmax Difference (BiasedMSD)

Typically, the final layer of a deep learning classification model is the softmax layer, which produces predictions for a given input. Ideally, the model should accurately replicate the ground truth of the input sample. However, in practice, an entirely perfect or ideal model is unattainable, and a prediction close to the expected ground truth is typically observed.

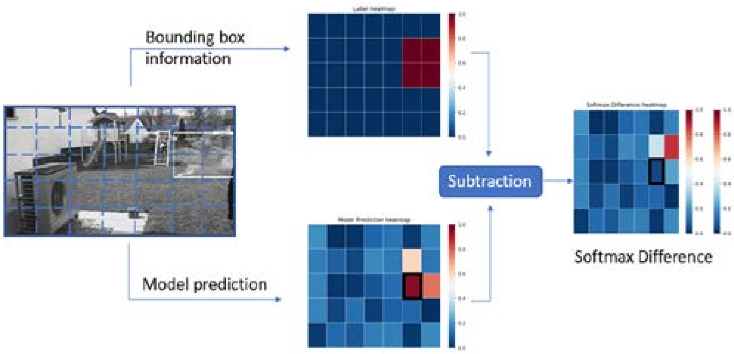

Fig. 3 Illustration of BiasedMSD approach. The difference between the model prediction (mid-bottom) and the ground truths (mid-top) is performed and termed as softmax difference (Bold patch is the patch with maximum prediction and it's softmax difference is used for the whole frame).

The Biased Maximum Softmax Difference is another novel approach that is quite simple and easy to implement. The definition of uncertainty that is adopted in this approach is the distance between the ground truth and reality. For the patch-wise classification problem, as the prediction obtained is patch-wise, the softmax difference is also obtained patch-wise for individual frames.

The drawback of the approach is that one needs the labels beforehand to estimate uncertainty. Due to this shortcoming and the requirements of the labels beforehand, the method is called **B**iased **M**aximum **S**oftmax **D**ifference (BiasedMSD), while the bias of requiring ground truth is present for estimating the uncertainty. The visual representation of the working of the BiasedMSD is illustrated in Fig. 3. The inherent bias to require labels for uncertainty estimation suggests that the method may only be used for curating labeled data.

3.3 Active Learning

The final step of the methodology in the scenario of Active Learning (AL) encompasses the implementation of all previously described efficient methods. AL initiates with random sequences in the training dataset, while the remaining data is stored in the pool set. The central concept of AL involves adding a budget (k) of samples or videos to the training set iteratively and removing samples from the pool set. As a result, the iterative process leads to an increase in the size of the training set and a decrease in the size of the pool set. The training of the model is performed on a set of training data, and the methods for estimating uncertainty are utilized to compute scores of uncertainty. The top-k selection for video-based data can be performed using two distinct approaches.

3.3.1 Sequence-wise selection

The **s**equence-**w**ise (SW) selection method involves selecting the whole video or sequence. Since uncertainty estimation is performed on individual frames, a sampling strategy is employed to aggregate the frame-wise uncertainty estimates into sequence-wise estimates. These sequence-wise uncertainty estimates are then ranked, and the top k sequences are selected. However, this approach may be influenced by a limited number of uncertain frame samples within a video, leading to a bias towards those samples.

3.3.2 Frame-wise selection

The **f**rame-**w**ise selection (FW) method directly ranks the frame-wise uncertainty estimates, and the top-k frame samples are selected. This approach eliminates the need for a sampling strategy, as the frame-wise uncertainty estimates are directly considered.

After the top-k selection, the samples or videos selected from the pool set are added to the training set and removed from the pool set as illustrated in Fig. 1. This whole process is repeated in an iterative manner.

4. EXPERIMENTATION

We conduct different experiments to evaluate and compare the performance of various uncertainty estimation methods in the context of Active Learning. Inception-v1 (Szegedy, *et al.* 2014) was used as a model backbone architecture and the input video was resized into the shape of (640, 360) grayscale images. We use Adam optimizer while training the model.

4.1 Evaluation Metric

In general, object detection algorithms are evaluated using mean Average Precision (mAP) which requires the computation of Intersection over Union (IoU) over the bounding boxes. But the model implemented in the research does not provide bounding box information as an output of the model, but rather a patch-wise classification. Hence, the Receiver Operating Characteristic (ROC) (Streiner & Cairney, 2007) curve has been adopted for performing the model evaluation. ROC curve is computed by evaluating the predictions of the model over different thresholds, and plotting True Positive Rate (TPR) and False Positive Rate (FPR) for each threshold in a curve. As in realistic applications, the FPR should be very low in order to avoid a large number of false alarms. Hence, the Area Under the ROC Curve value under the threshold of 2% FPR ($AUC_{2\%}$) is evaluated and used as a metric to evaluate different methods.

4.2 Uncertainty Estimation Comparison

We performed an analysis of the cost comparison for uncertainty estimation for videos ranging from 1 to 2000. As depicted in Fig. 4, the initial cost of deep ensembles is substantially greater than that of other methods. The State-of-the-Art FacerDir method exhibits a slightly greater initial cost relative to the conventional MCD, MCDB, and TTA approaches. However, for a higher number of video estimations, the method proved to be substantially more efficient.

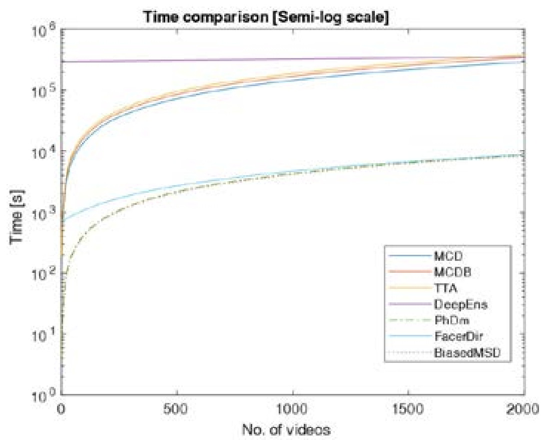

Fig. 4 Time comparison for uncertainty estimation for different methods. The plot represents the time required to estimate uncertainty using different methods over 2000 cumulative videos.

The novel proposed PhDm and BiasedMSD-based uncertainty estimation methods exhibit the least overhead time overall. The FacerDir, PhDm, and BiasedMSD-based uncertainty estimation methods exhibit considerably low overhead costs, indicating a promising opportunity to advance toward the subsequent phase of incorporating an active learning for data curation.

4.3 Baselines for Data Curation

Active learning is performed iteratively till the quarter of the informative/uncertain dataset is sampled. The model is later trained on the sampled informative training data and the following baselines are used for comparing the model performance:

4.3.1 Baseline for pool data curation

Pool data curation is one of the main purposes of active learning, while the most informative data is curated for annotation using a sampling strategy. The function *a(x)* is defined as a draw from a uniform distribution over the interval [0, 1] using the function (Gal, *et al.* 2017). This criterion ensures that the selection strategy for acquiring annotated data is superior to a random selection approach and is used in majority of scientific studies.

4.3.2 Baseline for train data curation

Active learning is seldom used in the literature to curate the training data as it is always seen as a method to curate the unknown pool data. In our research, an active learning approach was utilized to curate the training dataset with the objective of mitigating potential implicit biases that may exist within the data. The assessment and comparison of various approaches are based on the performance of the primary network, which is trained on the complete dataset utilized for active learning experimentation. In the event that the active learning technique produces a subset of the training dataset that surpasses the primary network's performance, it can be utilized for training data curation in a general context.

4.4 Active Learning for Data Curation

We conduct a series of experiments on three different data filter sizes viz. 15, 30, and 60 randomly filtered **f**rames **p**er **s**equence (fpseq). It is in-feasible to perform the experiments on the full internal dataset and hence, for research experimentation three different data filter sizes were randomly developed. It is important to note that the comparison of the metric over different data sizes internally is not possible as the data was randomly selected.

The uncertainty estimation was performed using PhDm, BiasedMSD, and FacerDir. The uncertainty estimation was iteratively used in an AL setting to sample top uncertain samples. The uncertain samples were iteratively added and removed from the training and pool dataset, respectively. The uncertainty sampling for PhDm and FacerDir-based approaches were done using **S**equence-**w**ise (SW) and **F**rame-**w**ise (FW) querying strategies. Fig. 5 represents the comparison of the performance of different experiments over various data sizes.

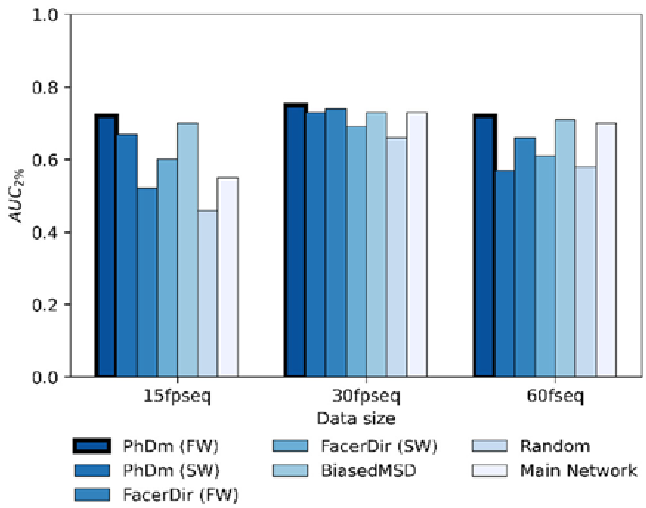

Fig. 5: AL method performance comparison for different methods applied over various filtered data sizes (bold bar represents best performing method). FW and SW represent Frame-wise and Sequence-wise querying strategies.

5. DISCUSSION

Fig. 4 illustrates the overhead cost associated with uncertainty quantification. It can be observed that the utilization of PCA and biased differencing-based techniques resulted in relatively shorter estimation times. This observation suggests that the proposed novel methods in the paper exhibit significantly lower overhead uncertainty estimation costs in comparison to the conventional and State-of-the-Art distillation approaches.

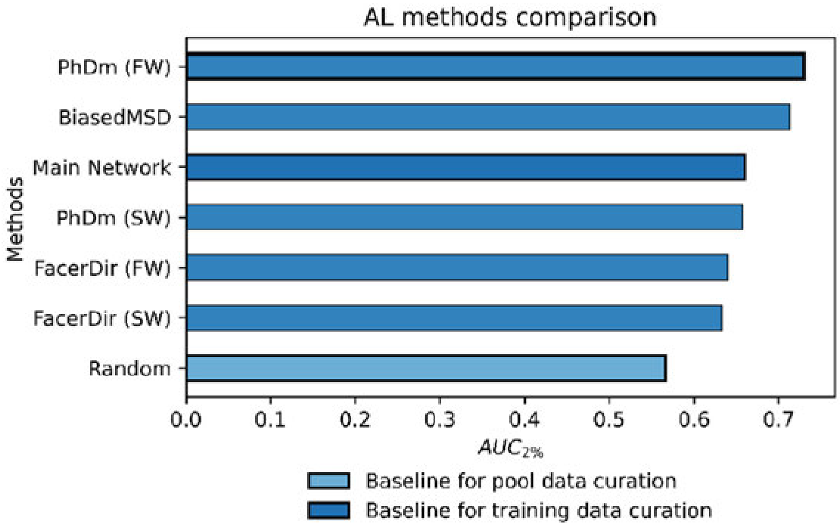

Fig. 6 Performance comparison of different AL methods. The random network is the baseline for pool data curation and the main network is the baseline for training data curation. The novel PhDm approach performance outperformed the random and main network baseline.

It is evident from Fig. 6 that the novel PCA-based method outperformed other AL approaches in the context of training and pool data curation. The overall comparison of different AL approaches is illustrated in Fig. 6 . It is evident from the figure that the frame-wise selection approach was generally better than the sequence-wise querying strategy. The frame-wise selection of images from the videos proved to perform efficiently compared to selecting the whole sequence at a time using a sequence-wise selection strategy. The frame-wise querying strategy improved the performance of the PCA-based active learning method by 7.33% and the FacerDir approach by 0.67%. This finding can be utilized to crop informative frames from different excessively long videos, which is an intriguing application of the active learning strategy. In general, every method outperformed the Random baseline. This indicated that every method performed well in the context of pool data curation and annotating the pool data using uncertainty quantification.

In every experiment conducted using varying data sizes, the novel PhDm approach outperformed the main network, despite utilizing only 26.39% of the available data for model training. The approach improved the performance of the model architecture compared to the random baseline with 16.33% of $AUC_{2\%}$ evaluation metric. The approach even improved the main network performance by 7.33% and outperformed other approaches. These findings suggest that the PhDm approach can achieve superior performance with significantly fewer training data as compared to the main network and is an approach with a very low overhead uncertainty quantification cost.

BiasedMSD selects challenging data instances that the model struggles to comprehend as uncertain samples. Therefore, this approach is expected to yield superior uncertainty estimation results and excel in AL scenarios. By including image samples that the model has identified as false positives, the approach can effectively enhance data quality. The BiasedMSD approach improved main network performance by 5.66%, however, the improvement was not as evident as seen in the PhDm approach. The performance of FacerDir-based active learning was found to improve the network by 7.33% than the random baseline compared to a significant 16.33% improvement using the novel PCA-based hard data mining approach.

Recapitulating the results observed in the experiments, the feature-based novel approach outperformed other approaches in the context of curating pool and training data using AL. This is attributable to the fact that the feature-based approach captured more information about the samples than sampling a probability distribution over several forward passes.

6. CONCLUSION

This paper focuses on the various uncertainty estimation techniques for the object detection-based fire detection problem with an aim to curate the data. We proposed two novel approaches for curating the data using active learning. The novel PhDm and BiasedMSD approaches performed uncertainty estimation efficiently compared to the sampling-based methods and the State-of-the-Art FacerDir. The novel approaches were also found to outperform other benchmark methods in the task of curating the unlabeled data. PhDm was found to be the most efficient method for curating and improving the training data by decreasing the size of the training.

Finally, we put forward potential avenues for future research exploration. Different uncertainty and active learning experiments were performed in the setting of binary classification. The experimentation on multi-class classification problems can be done using the novel approaches stated in the literature. The novel AL techniques can be further evaluated on various publicly available datasets.

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IDENTIFYING HAZARDS IN CONSTRUCTION SITES USING DEEP LEARNING-BASED MULTIMODAL WITH CCTV DATA

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ABSTRACT: *The use of closed-circuit television (CCTV) for safety monitoring is crucial for reducing accidents in construction sites. However, the majority of currently proposed approaches utilize single detection models without considering the context of CCTV video inputs. In this study, a multimodal detection, and depth map estimation algorithm utilizing deep learning is proposed. In addition, the point cloud of the test site is acquired using a terrestrial laser scanning scanner, and the detected object's coordinates are projected into global coordinates using a homography matrix. Consequently, the effectiveness of the proposed monitoring system is enhanced by the visualization of the entire monitored scene. In addition, to validate our proposed method, a synthetic dataset of construction site accidents is simulated with Twinmotion. These scenarios are then evaluated with the proposed method to determine its precision and speed of inference. Lastly, the actual construction site, equipped with multiple CCTV cameras, is utilized for system deployment and visualization. As a result, the proposed method demonstrated its robustness in detecting potential hazards on a construction site, as well as its real-time detection speed.*

KEYWORDS*: deep learning, multimodal, multiCCTV, synthetic data, pointcloud*

1. INTRODUCTION

Construction sites are dynamic and complex environments that pose significant safety risks, resulting in an high rate of accidents and fatalities worldwide (Abdelhamid & Everett, 2000). Consequently, implementing effective safety monitoring measures is vital for reducing such incidents. The use of closed-circuit television (CCTV) cameras for safety monitoring on construction sites has played a crucial role in mitigating risks. Despite this, the full potential of CCTV data is often underutilized, primarily due to the majority of existing approaches employing single detection models without considering the full context of CCTV video inputs (Park et al., 2022, 2023; Tran et al., 2020). In response to this issue, this study proposes a novel and robust system that incorporates a multimodal detection and depth map estimation algorithm, utilizing the power of deep learning. The distinctiveness of our approach lies in the context-aware analysis, providing a more comprehensive understanding of the potential hazards present within the dynamic environments of construction sites. Furthermore, our proposed method goes a step further by leveraging terrestrial laser scanning technology to acquire the point cloud of the test site and utilizing a homography matrix to project the detected object's coordinates into global coordinates. This step enhances the overall monitoring system's effectiveness by visualizing the entire monitored scene, thus providing a bird eye view of the potential hazards. A crucial aspect of any newly proposed system is rigorous validation. For our method, we have created a synthetic dataset of construction site accidents using Twinmotion, a high-powered graphic software. This dataset provides a range of simulated scenarios to test the precision and inference speed of our proposed method, ensuring its reliability and robustness in varied contexts.

Finally, we further validate our method by deploying it on an actual construction site equipped with multiple CCTV cameras, moving beyond simulations to a real-world setting. This on-site implementation allowed us to assess the practicality of our system and its ability to function optimally in an uncontrolled, real-world environment. The results from both simulation and real-world deployment demonstrate our proposed method's

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Dai Quoc Tran, Yuntae Jeon, Seongwoo Son, Minsoo Park, Seunghee Park, *Identifying Hazards in Construction Sites Using Deep Learning-Based Multimodal with CCTV Data,* pp. 625-633, DOI 10.36253/979-12-215-0289-3.61

robustness in detecting potential hazards on a construction site. This paper aims to highlight the potential of multimodal detection approaches in enhancing construction site safety measures, moving towards a future where such hazards can be preemptively detected and effectively mitigated. In the following sections, we will provide a detailed explanation of our proposed method, its development, and the validation process. We will also present the results and implications of this study, demonstrating how a deep learning-based multimodal approach can be used for safety monitoring in the construction industry.

2. BACKGROUND

This section provides the necessary background on the key aspects of our methodology, namely object detection, depth estimation, and multimodal synchronization. These three components collectively constitute the core of our proposed method and are fundamental in understanding the context-aware safety monitoring approach.

2.1.Object Detection

Object detection, as a fundamental component of computer vision, has undergone significant developments over the past decade, thanks to the advancements in deep learning and convolutional neural networks (CNNs) (Li et al., 2021). This involves identifying and locating objects within images or video feeds. In construction sites, object detection can identify critical elements such as workers, machinery, tools, and other potential hazards, thereby playing a vital role in safety monitoring. However, traditional object detection models typically operate independently, failing to incorporate the broader context of a scene (Jeon et al., 2023; Tran et al., 2022). These models often struggle with complex environments like construction sites, where multiple objects interact dynamically, and understanding these interactions is crucial for effective hazard detection. This limitation forms the motivation for our study, aiming to integrate a higher level of contextual understanding into object detection models using deep learning algorithms. In this research, two state of the art object detection models are utilized: Yolov8 (Redmon et al., 2016) and RTMDet (Lyu et al., 2022). These two object detectors are trained and validated in actual CCTV images and utilized for incorporation with other models.

2.2.Depth Estimation

For understanding context of input image, spatial information is crucial, therefore, a depth estimation model MiDAS (Ranftl et al., 2020) is utilized. Depth estimation refers to the task of determining the relative distance of objects within a scene from the viewpoint of the camera. It is a crucial component in understanding three-dimensional spaces from two-dimensional images or video feeds, providing invaluable information about the positioning and interaction of objects within a scene. In construction sites, depth estimation can enhance the understanding of spatial relations among various elements, such as the proximity of a worker to a moving machine, thereby aiding in detecting potentially hazardous situations. This paper incorporates depth estimation into our proposed multimodal approach, further improving the context-awareness of the system.

2.3.Multimodal Synchronization

Incorporating multimodal synchronization into safety monitoring has the potential to significantly enhance the effectiveness of hazard detection. For example, a hazard that is not visible from one camera angle may be clearly observable from another. Similarly, certain hazardous situations may only be identifiable when considering multiple factors, such as the positioning and motion of various objects, which could be obtained from different data sources. In our proposed method, we aim to utilize multimodal synchronization to integrate object detection and depth estimation data, along with point cloud data obtained through terrestrial laser scanning. This synchronization allows for the projection of detected objects into global coordinates, enhancing the visualization of the entire monitored scene and thus the system's overall effectiveness. In the subsequent sections, we will elaborate on the implementation of these components in our proposed method and demonstrate their effectiveness in enhancing construction site safety monitoring.

3. PROSED APPROACH

3.1.Proposed approach

Figure 1 depicts the proposed method as follows: First, the input image is predicted using object detectors that have been pretrained. In this study, an object detector that can infer six classes is described in detail, along with the training procedure and training dataset. In addition, the MiDAS model is used to estimate the depth map using a previously trained depth estimation model. The Euclidean distance between objects is then estimated and visualized with the given depth and bounding box coordinates, after which each object's depth map is extracted. This research considers the distance between construction machines and employees, as well as the module to estimate whether or not a worker is in the danger zone. In addition, work-related personal protective apparatus is trained and implied.

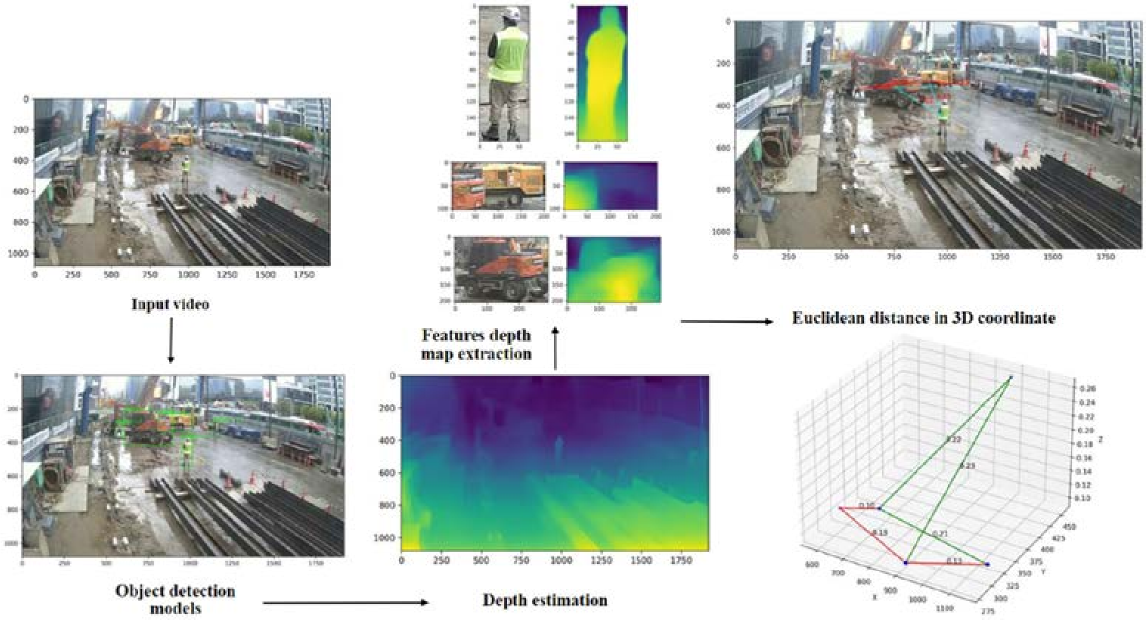

Figure 1. Proposed Approach

3.2.Dataset Acquisition

The training dataset contains bounding boxes objects from 6 classes: *normal worker, signalman, harness, hardhat, mixer truck and excavator*. As visualized in Figure 2, each object is labeled in detail from actual CCTV footage. Figure 3 presented a training and testing dataset classes distribution.

Figure 2. Dataset visualization

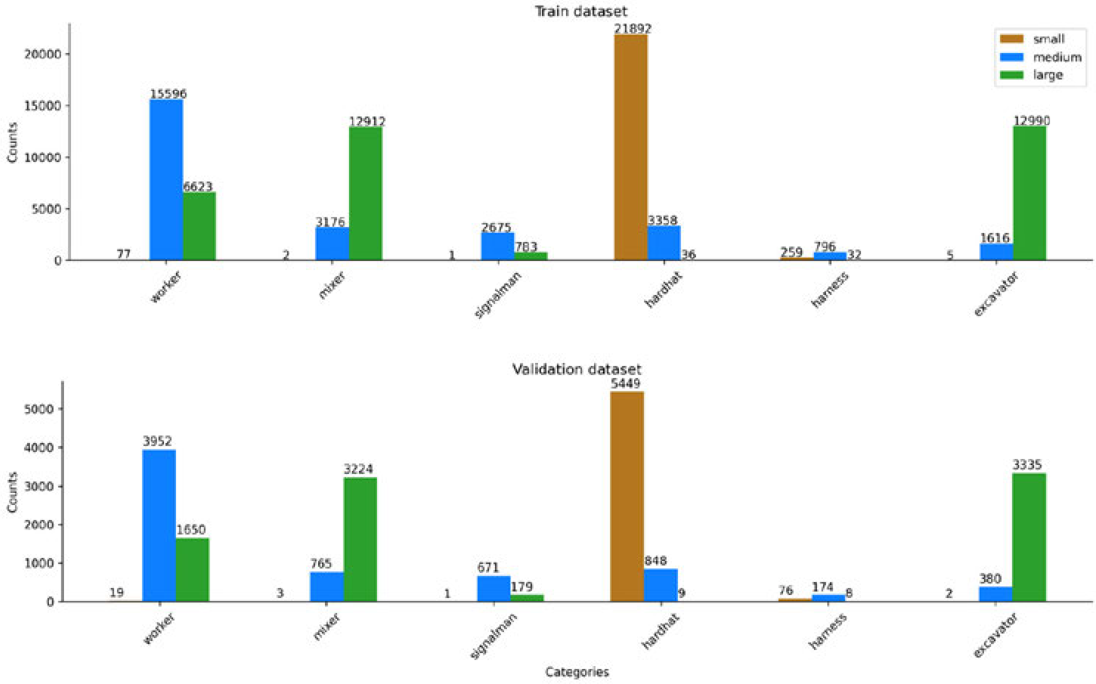

Figure 3. Training and testing dataset distribution. The y-axis depicts the total of each class in training and testing datasets. The x-axis lists the distinct class names or labels in dataset. In our case, these are: “worker”, “mixer”, “signalman”, “hardhat”, “harness”, and “excavator”.

For evaluate model performance, the detected objects are categorized into 3 types: "small", "medium", and "large" follows a specific definition based on the number of pixels occupied by an object in an image. Specifically, objects are categorized as follows:

- "Small": Objects occupying 0 to 1024 pixels, which translates to dimensions up to 32 × 32 pixels.
- "Medium": Objects occupying between 1024 and 9216 pixels, which corresponds to dimensions between 32 × 32 and 96 × 96 pixels.
- "Large": Objects occupying more than 9216 pixels, equating to dimensions of 96 × 96 pixels or larger.

With these categorizations, our dataset reflects an essential aspect of object detection tasks: dealing with objects of varying sizes. The balance or imbalance of different categories may significantly affect the predictive performance of an object detection model. In our dataset, categories such as "mixer" and "excavator" contain a substantial number of "medium" and "large" objects. Conversely, the "hardhat" category is predominantly composed of "small" objects. This imbalance suggests that an object detection model trained on this data might develop a bias toward detecting "medium" or "large" objects and underperform on "small" objects.

4. Experimental

4.1.Quantitative

Table 1. Object detectors performance.

	mAP	**mAP_50**	**mAP_75**	**mAP_s**	**mAP_m**	**mAP_l**	**Flops**
YOLOv8X	0.689	0.831	0.741	0.123	0.733	0.811	0.129T
RTMDet	0.628	0.776	0.688	0.059	0.641	0.756	79.964G

In order to quantify the results, the mean average precision (mAP) is employed as an evaluation metric. The mAP is a widely recognized indicator used to quantitatively assess the performance of object identification models. The research provides a comprehensive explanation of the mAP (Zhao et al., 2019). As presented in Table 1, YOLOv8X and RTMDet, with regard to their performance metrics, a notable variance in their effectiveness becomes clear. The YOLOv8X model exhibits superior precision with a mAP score of 0.689, which considerably exceeds the 0.628 mAP score of the RTMDet model. This indicates an overall higher rate of accurate detections by the YOLOv8X model. Further disparity can be observed at varying Intersection over Union (IoU) thresholds. The mAP_50 and mAP_75 scores, which represent the mAP values computed at IoU thresholds of 0.50 and 0.75 respectively, demonstrate a superior adaptability of the YOLOv8X model to changes in detection difficulty levels. When checking the mAP values across different object sizes, denoted by mAP_s (small), mAP_m (medium), and mAP_l (large), the YOLOv8X model continues to display superior performance. The model's proficiency in detecting small objects is particularly noteworthy, with a score of 0.123 compared to the RTMDet's score of 0.059. Nevertheless, it is crucial to consider the computational complexity of the models. RTMDet has a significant advantage in this regard, with a computational demand of 79.964G Flops, markedly lower than the YOLOv8X's 0.129T (or 129,000G) Flops. This positions RTMDet as a more feasible option for applications with limited computational resources, despite its inferior mAP performance. While the YOLOv8X model outperforms RTMDet in terms of object detection performance across various metrics, the latter's significantly lower computational demand may make it a more suitable candidate for resource-constrained applications. The selection between these two models, therefore, necessitates careful consideration of the balance between performance efficiency and resource utilization, contingent on the specific requirements of the application.

4.2.Qualitative

As mentioned in previous sections, after detecting objects, the depth map is estimated and calculating the distance between worker and construction vehicles. As can be seen from Figure 4, by utilizing spatial information, the distance can be estimated and from that, the necessary warning can be conducted.

Figure 4. Distance estimation using depth estimation and object detection.

Figure 5 showed another application of the proposed approach by identifying which workers are in the danger area. The danger area is defined by the safety officer, and when detected worker violate that area, the number of violated cases will be shown and reported directly to safety manager. Along with detecting worker, a PPE detection models also consider to utilized, as can be seen from Figure 6, both hardhat and harness is detected for checking. To reduce the false positive, we remove detected PPE outside of the worker detected area, as can be seen in Algorithm 1.

Algorithm 1. Detecting PPE

```
Lqsxw=#Lpdjh#L#
Rxwsxw=#Glvsod|hg#erxqglqj#er{hv#ri#ghwhfwhg#vdihw|#htxlsphqw#rq#shuvrqv#
#
4=#surfhgxuh#VDIHW\bHTXLSPHQWbGHWHFWLRQ+L,#
5=#####shuvrqPrgho#?0#Lqlwldol}h#suhwudlqhg#prgho#iru#shuvrq#ghwhfwlrq#
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7=######
8=#####shuvrqErxqglqjEr{hv#?0#shuvrqPrgho1ghwhfw+L,#
9=#####vdihw|HtxlsphqwErxqglqjEr{hv#?0#vdihw|HtxlsphqwPrgho1ghwhfw+L,#
:=######
;=#####iru#hdfk#shuvrqEr{#lq#shuvrqErxqglqjEr{hv#gr#
<=#########iru#hdfk#htxlsphqwEr{#lq#vdihw|HtxlsphqwErxqglqjEr{hv#gr#
43=#############LrX#?0#FDOFXODWHbLRX+shuvrqEr{/#htxlsphqwEr{,#
44=###############
45=#############li#LrX#A#318#wkhq#
```

```
46=##################GLVSOD\bERXQGLQJbER[+htxlsphqwEr{/#L,#
47=##############hqg#li#
48=##########hqg#iru#
49=#####hqg#iru#
4:=#hqg#surfhgxuh#
```

Figure 5. Detect workers in the danger area

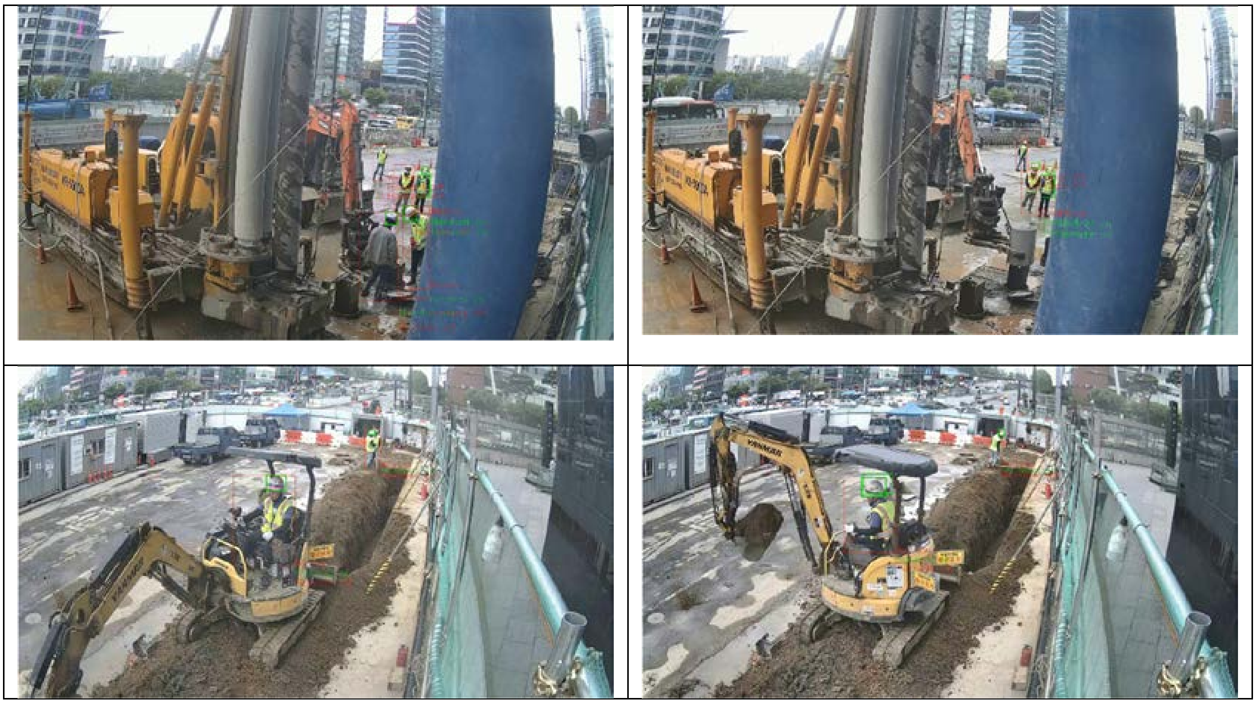

Figure 6. PPE detection

Finally, for developing multi-CCTV and bird eye view (BEV) synchronization. Two cases of examples are conducted as follows: first, by utilizing TwinMotion, the 4 CCTV channel is developed and used as an input for detection models, with homography matrix, the BEV is shown in Figure 7.

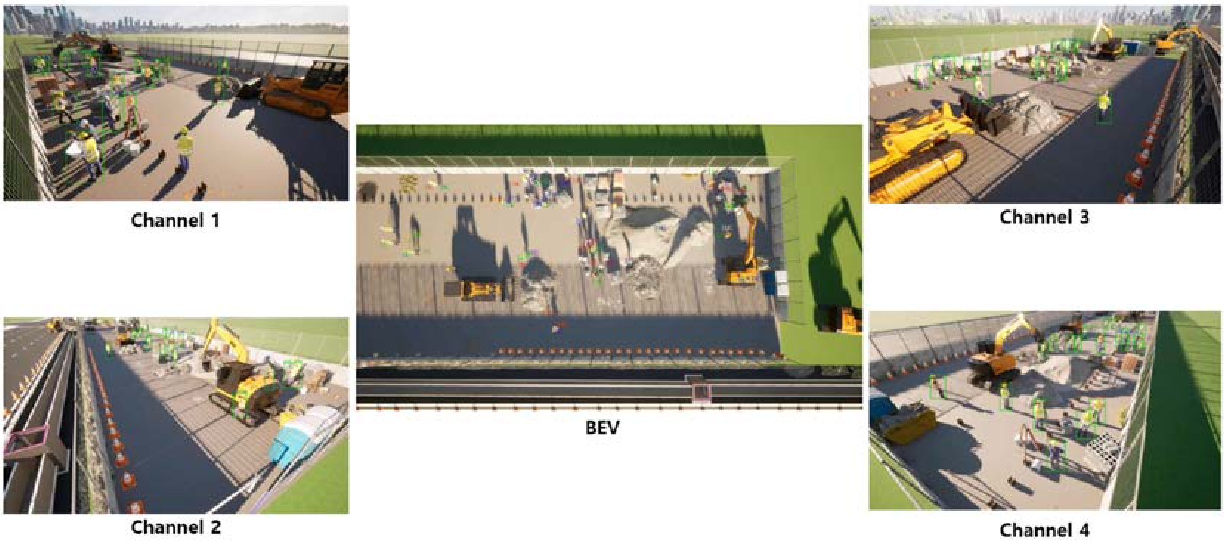

Figure 7. Multi CCTV with BEV in Twinmotion

Similarly with above example, but in actual construction site, it difficult to obtain BEV image, that why TLS is utilized for scanning and from that BEV can be estimated as shown in Figure 8 and 9. However, by only projecting all detected object into BEV, the exact ID of objects vary channels to channels. Therefore, the application of multi object detection and tracking can be used for future research. The expected output is given multi-channel CCTV, the output is the BEV with exact number and ID of detected objects. This study mostly emphasizes qualitative experiments. In order to obtain quantitative results, the forthcoming experiment will be undertaken by establishing an indoor environment and thereafter measuring the error projection using a meter.

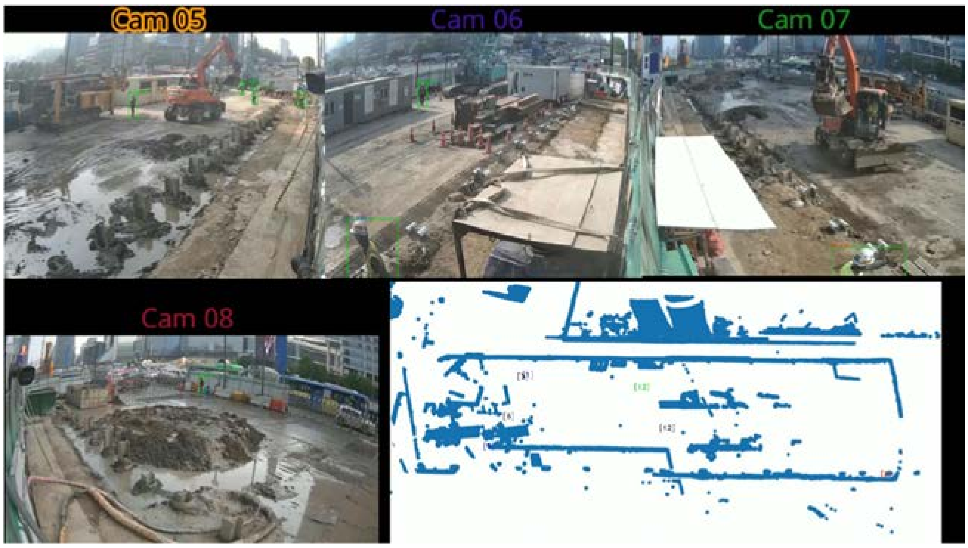

Figure 8. Multi CCTV with BEV in actual construction site

Figure 9. Multi CCTV with BEV in actual construction site

5. CONCLUSION

By adopting a multimodal detection approach, the study proposes a depth map estimation algorithm designed to enhance the contextual understanding of video inputs from CCTV. The proposed method uses terrestrial laser scanning to generate a point cloud of the test site and leverages a homography matrix to project detected objects into global coordinates. With object detection models used in the proposed method, a detailed analysis of YOLOv8X and RTMDet was conducted. YOLOv8X exhibited superior precision across various measures, including overall mAP, mAP at varying IoU thresholds, and mAP across different object sizes. However, the RTMDet model was identified as more resource-efficient, demanding significantly fewer computational resources despite its lower mAP performance. This research also presented some use cases of multimodel detections, it proves that context-aware approach in safety monitoring is important and should be considered for further research.

6. ACKNOWLEDGEMENT

This research was supported by a grant from the Korean Government (MSIT) to the Research Foundation of Korea (NRF) [RS-2023-00250166]. In addition, this research was supported by a grant [2022-MOIS38-002 (RS-2022-ND630021)] from the Ministry of Interior and Safety (MOIS)'s project for the development of accident prevention technology for vulnerable groups.

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DEEP LEARNING-BASED POSE ESTIMATION FOR IDENTIFYING POTENTIAL FALL HAZARDS OF CONSTRUCTION WORKER

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ABSTRACT: *Fall from height (FFH) is one of the major causes of injury and fatalities in construction industry. Deep learning-based computer vision for safety monitoring has gained attention due to its relatively lower initial cost compared to traditional sensing technologies. However, a single detection model that has been used in many related studies cannot consider various contexts at the construction site. In this paper, we propose a deep learning-based pose estimation approach for identifying potential fall hazards of construction workers. This approach can relatively increase the accuracy of estimating the distance between the worker and the fall hazard area compared to the existing methods from the experimental results. Our proposed approach can improve the robustness of worker location estimation compared to existing methods in complex construction site environments with obstacles that can obstruct the worker's position. Also, it is possible to provide information on whether a worker is aware of a potential fall risk area. Our approach can contribute to preventing FFH by providing access information to fall risk areas such as construction site openings and inducing workers to recognize the risk area even in Inattentional blindness (IB) situations.*

KEYWORDS: *deep learning, keypoint detection, pose estimation, computer vision, construction site safe*

1. INTRODUCTION

Due to numerous hazards and safety challenges, the construction industry stands out as highly dangerous, characterized by elevated rates of accidents and injuries. Among these, falls from heights (FFH) emerge as a particularly frequent and urgent concern, often leading to severe injuries or fatal outcomes. These incidents underscore the inherent risks associated with construction activities, contributing to delays and economic setbacks (Rafindadi et al., 2022).

Despite the stringent enforcement of safety standards, comprehensive worker training, and the adoption of advanced protective equipment, FFH-related accidents persist at an alarming rate. A closer examination reveals that these mishaps frequently result from worker negligence, inadequate situational awareness, or an inability to recognize impending dangers (Golparvar-Fard et al., 2013). The dynamic and ever-evolving nature of construction sites further exacerbates these challenges, rendering many traditional safety measures ineffective.

Historically, human oversight and routine inspections have been the primary means of safety supervision in construction settings. However, these methods, being inherently subjective, often result in inconsistent safety assessments. Recognizing these limitations, there's been a shift towards leveraging emerging technologies such as computer vision and artificial intelligence (AI). While these innovations promise objective, consistent, and real-time safety evaluations, challenges remain. Specifically, detecting hazards like floor openings becomes complex due to occlusions from construction materials and scaffolding. Additionally, determining a worker's position, especially when parts of their body are obscured, remains problematic.

In light of these challenges, this study proposes a novel approach, integrating computer vision and deep learning, tailored for construction site safety evaluations. The essence of our methodology lies in the fusion of quadrilateral detection, pose estimation, and single depth estimation. Quadrilateral detection accurately captures the contours

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)

Minsoo Park, Seungsoo Lee, Woonggyu Choi, Yuntae Jeon, Dai Quoc Tran, Seunghee Park, *Deep Learning-Based Pose Estimation for Identifying Potential Fall Hazards of Construction Worker,* pp. 634-640, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.62

of target objects, pose estimation provides insights into their spatial orientation, and single depth estimation refines the distance measurements. By employing quadrilateral anchors, further enhanced by the Vision Transformer, our approach aims to provide a more robust and accurate tool for hazard detection and prevention.

The structure of this paper is as follows:

- Chapter 2 delves into relevant literature, providing a thorough assessment of existing approaches, their strengths, and inherent limits.
- Chapter 3 elucidates our proposed methodology, shedding light on its unique facets and potential advantages.
- Chapter 4 includes experimental results, including quantitative assessments as well as visual representations of our findings.
- Chatpter 5 concludes the paper by summarizing the paper and suggesting future avenues for research.

2. RELATED WORK

The construction industry has long grappled with the challenge of ensuring worker safety, especially in the context of falls from heights (FFH) (Helander, M. 1980). This section delves into the existing methods and recent advancements in recognizing unsafe areas and the application of deep learning in the construction site context.

2.1. FFH-related Safety Monitoring

Traditional safety measures, such as guardrails and safety nets, have been the primary defense against FFH incidents (Zhang, M. and Fang, D. 2013). However, the dynamic and complex nature of construction sites often renders these measures insufficient. The rapidly changing environment, coupled with the diverse nature of construction tasks, necessitates more advanced and adaptive safety solutions.

Historically, the realm of automated construction safety has leaned heavily on sensor-based mechanisms. Techniques like radio frequency identification (RFID) were the go-to solutions for monitoring workers' movements into potentially hazardous zones (Costin, et al., 2012). Similarly, tools like global positioning systems (GPS) and ultra-wideband (UWB) played pivotal roles in identifying unsafe regions and pinpointing the location of workers and materials (Pradhananga, N. and Teizer, J. 2013). However, the drawback of these methods was the necessity for individual sensor installations.

The modern era has seen a surge in the exploration of computer vision combined with deep learning as potential reasonable approach in safety area (Park, et al., 2020; Jeon, et al., 2023). Recent advancements in technology are poised to significantly transform the paradigm of worker safety through the automation of risk assessments. Noteworthy progress has been achieved in the application of computer vision to identify potential hazards (Tran, et al., 2022). However, some studies exhibit limitations in their scope, especially regarding the precise localization of dangers and the evaluation of workers' proximity to such hazards. In sight of these observations, there's a clear demand for a more refined approach that not only pinpoints hazards with precision but also factors in worker proximity in real-world scenarios.

2.2. Deep Learning and Computer Vision in Construction Environments

The dynamic and cluttered nature of construction sites poses unique challenges for deep learning models. The presence of obstructions like construction materials and scaffolding often disrupts the model's ability to accurately identify target objects. A popular solution, borrowed from interdisciplinary research, is the integration of attention modules. These modules enhance the model's feature extraction capabilities, emphasizing crucial aspects of images.

Recent research has showcased the potential of attention mechanisms in improving detection accuracy, especially in environments where objects are either partially hidden or appear smaller due to perspective. For instance, several works refined the triplet attention mechanism, assigning greater significance to vital features. This refinement allowed models to zero in on specific image sections, enhancing the accuracy of worker detection, even in intricate construction settings. Their model could pinpoint a worker's approximate location, even if they were partially obscured. Another noteworthy approach is the use of distance intersection over union (DIoU) based on non-maximum suppression (NMS). This technique distinguishes between overlapping objects against the complex backdrop of construction sites.

However, these methods are not without their limitations. For instance, if a worker's lower body is entirely obscured, the detection only captures the visible sections. This makes it challenging to determine a worker's exact position based solely on bounding box coordinates.

Enter pose estimation, a more adaptable solution to traditional object detection challenges posed by occlusions. Recent advancements in the intersection of construction safety and computer vision have highlighted its promise. By leveraging pose estimation, researchers have been able to identify unsafe work postures and ensure the proper use of safety equipment.

Despite its potential, few have explored pose estimation to determine construction worker locations, especially considering obscured body parts. Moreover, basic detection methods, which don't account for distance, only identify the presence of workers and hazards without gauging the relative proximity between them. This limitation hampers their ability to issue timely warnings to workers approaching danger zones.

The Vision Transformer model, applied to depth estimation, demonstrated the capability of assessing object depths and distances with a singular camera (Ranftl, et al., 2021). However, with increasing distances, the differentiation in depth becomes less discernible, potentially limiting its utility for comprehensive construction site surveillance. In conclusion, there is a pressing need for cost-effective computer vision techniques that can not only pinpoint worker locations but also preemptively warn them about impending hazards.

3. METHODS

To address the identified challenges, we propose a comprehensive methodology that leverages advanced computer vision and deep learning techniques. Our methodology consists of two main components: detection of floor openings using a quadrilateral-anchor-based Vision Transformer, and estimation of worker positions using a pose estimation approach.

3.1 Baseline Detection Architecture

Given the urgent and real-time nature of risk management on construction sites, it is imperative to employ a model that can provide immediate and accurate monitoring. YOLOv7 is boasting high accuracy while maintaining real-time capabilities in real time detection (Wang, et al., 2023). While minor trade-offs in FPS might occur, extending YOLOv7 with additional models presents an avenue for enhancing accuracy. In view of these considerations, YOLOv7 was chosen as the foundational model for our study.

3.2 Attention Mechanism

The introduction of the attention mechanism has proven transformative in object detection tasks. By dynamically emphasizing salient image features while downplaying less informative ones, models exhibit enhanced capacity for accurate object detection and classification, all while preserving the efficiency of the detection process (Park, et al., 2022; Guo, et al., 2022). Traditional attention methods, including squeeze-and-excitation (SE) (Hu, et al., 2018) and convolutional block attention mechanism (CBAM) (Woo, et al., 2018), utilize convolutional neural networks to recalibrate feature maps, enhancing model accuracy and robustness by prioritizing meaningful information over less relevant components.

3.3 Polygon Anchor for Object Detection with Vision Transformer

The detection of floor openings is achieved through a convex quadrilateral-anchor-based Vision Transformer. This approach allows for accurate detection of floor openings, even when the camera perspective is not aligned with the floor opening as shown in Figure 1. The quadrilateral anchors allow for more flexibility in defining the bounding boxes, enabling them to closely match the actual boundaries of the floor openings. The Vision Transformer is used to extract both the global dependencies between the floor openings and other parts of the building and the local features specific to the floor openings. This combination of global and local feature extraction enhances the detection performance of the floor openings.

These two components, when combined, allow for a comprehensive, real-time monitoring of safety on construction sites. They enable not only the detection of floor openings but also the identification of unsafe zones and the real-time tracking of worker positions. This comprehensive safety monitoring can significantly enhance the safety at construction sites.

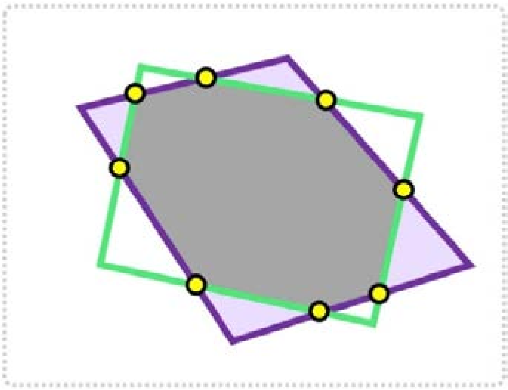

Fig. 1: Using convex quadrilateral anchors to detect floor openings. The purple boxes represent the ground truth, while the green boxes represent the predicted boxes. The overlapping area between the two boxes, indicated by yellow dots, is used to calculate the IoU (Intersection over Union).

3.4 Integrated Model for Floor-Opening Detection

we incorporate the YOLO-pose model (Maji, et al., 2022), which enhances YOLO capability to predict human poses. This model leverages pose estimation to refine object localization, offering a more comprehensive understanding of worker positions and orientations in relation to floor openings. This integration aims to amplify the focus on critical features and supply a more comprehensive contextual representation of images. This augmentation potentially heightens the efficacy and precision of our object detection model.

The envisioned integrated model aims to capture both local attributes and global interdependencies of floor openings. Local characteristics encompass attributes like shape, size, and color, facilitating nuanced comprehension and enabling their integration with other objects. Meanwhile, global interdependencies offer a holistic understanding of image constituents. For instance, floor openings often correlate with specific building elements, such as slabs, and a global outlook can encapsulate contextual information on a broader scale. This approach not only bolsters the perception of individual components but also provides insights into the overall building structure and floor opening placements.

3.5 Estimation of Relative Distances Between Workers and Danger Zone

Ensuring safety on construction sites entails assessing the proximity of workers to potential hazards, in this case, openings or drop-offs. Our method employs a combination of pose estimation and depth estimation to achieve this.

Firstly, we leverage the pose estimation of workers, specifically focusing on the leg parts, to gauge the distance, denoted as D. The rationale behind this focus is that the legs are often the closest body parts to openings or drop-offs and thus serve as critical indicators of a worker's proximity to these hazards.

Once D is determined, we then identify areas within a radius of D from detected openings as "hazard zones." Any worker located within this zone is considered at risk, warranting immediate safety interventions. Also, In the context of drop-offs, we utilize single depth estimation. When a detected individual's depth estimation result exhibits a drastic change, indicating proximity to areas with significant depth differences, they are deemed to be in a hazardous zone. Essentially, if a worker is close to an area where the depth changes abruptly, it is considered a potential fall hazard.

By integrating pose and depth estimations, our approach provides a comprehensive measure of potential risks, enabling proactive safety measures on construction sites.

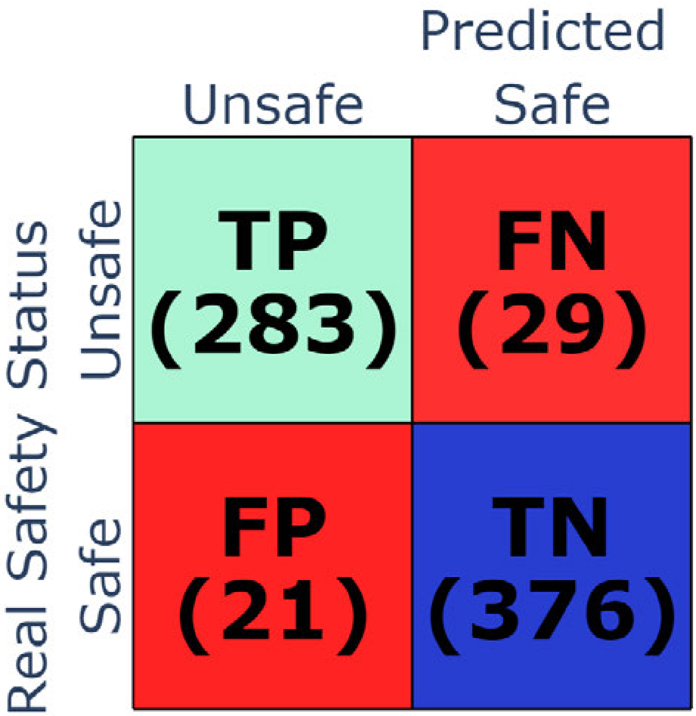

Fig. 2: The results of confusion matrix for the safe/unsafe decision making in construction site.

4. RESULTS

For our experiments, data were collected from both real construction sites and 3D simulation models. We specifically gathered images and videos of workers situated near openings and drop-offs where safety measures were not adequately implemented. In total, 3545 datasets were collected. We then employed a training-validation-test schema with a split ratio of 3:1:1, respectively, to evaluate our model's performance. The proposed method not only improves the detection of floor openings but also estimates the relative distance between the workers and the openings. The method defines unsafe zones around the openings based on this relative distance and provides real-time warnings to the workers when they enter these zones. The experiments also demonstrate the robustness of the proposed method in handling the complex and dynamic environment of construction sites.

The quantitative accuracy of the alert for FFH prevention at openings and edges from the proposed method is represented in Fig. 2, visualized using a Confusion matrix. We used a confusion matrix to assess the performance of our model in predicting whether a worker is in a hazardous zone or a safe zone. In real construction sites, due to the inherent nature of the environment, most of the samples were from safe zones, which explains the higher number of safe situation. By testing in both real and virtual environments, we ensured a comprehensive evaluation of our model's performance across diverse scenarios. Our model achieved an accuracy of approximately 93.2%, representing the proportion of total predictions that were correct. The precision of the model was 93.1%, indicating that when our model predicted a worker to be in a hazardous zone, it was correct about 93.1% of the time. The recall was valued at 90.7%, showcasing that our model correctly identified 90.7% of all actual hazardous situations. Harmonizing precision and recall, the F1-Score was found to be 91.9%. Fig. 3 visualizes the inference results of the models used in the proposed methodology. The final decision on risk/safety is automatically determined through post-processing from a combination of three algorithms.

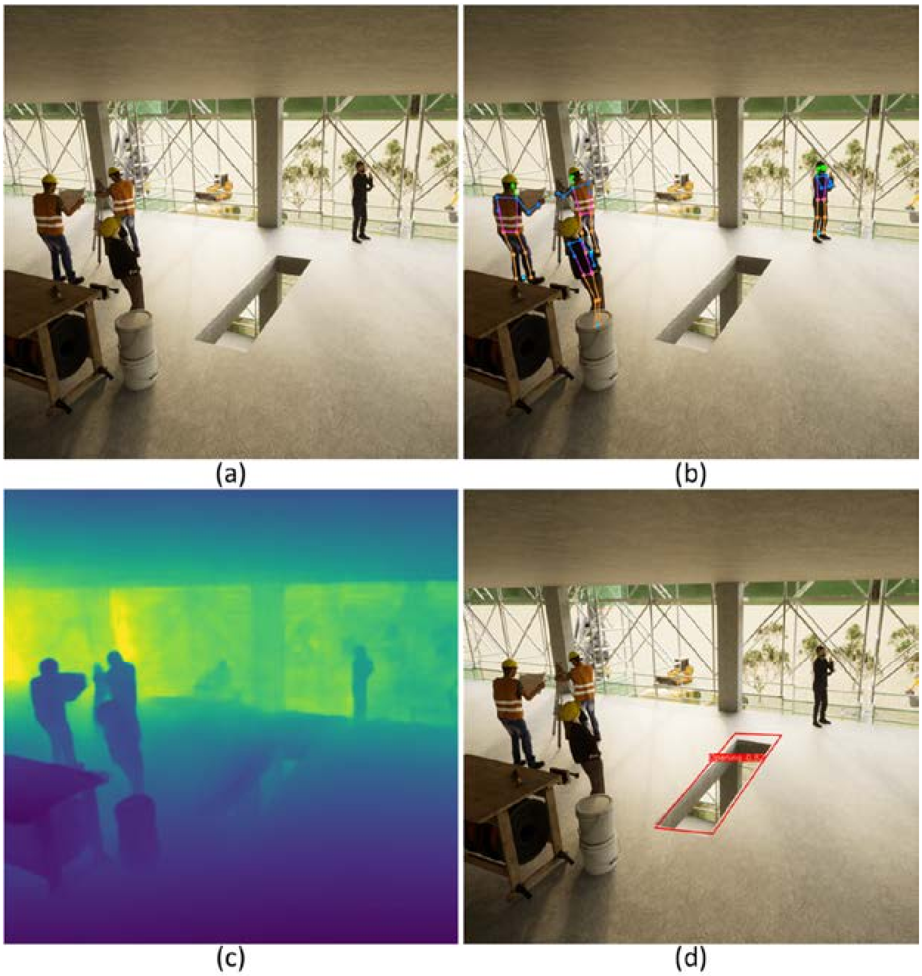

Fig. 3: Results of computer vision models in simulated hazardous situations for openings and edges using Unity. (a) Original image, (b) Pose estimation results, (c) Depth estimation results from a single camera, (d) Polygon detection results for floor openings.

5. CONCLUSIONS

This study presents a pivotal advancement in automated safety monitoring within the construction domain. By harnessing state-of-the-art computer vision and deep learning paradigms, our method adeptly detects floor openings and estimates the proximity of workers, facilitating real-time risk assessment. The potential to preempt accidents and heighten safety through this methodology is profound.

However, our study acknowledges certain limitations. Notably, while our method is primed for detecting risks, it may register false positives, especially in scenarios where floor openings function as stairs or access points, and workers are expectedly moving in and out. Conversely, false negatives can manifest when workers operate beyond a specific distance from the camera, rendering them undetectable. As per the feedback, it's crucial to clarify that we haven't explicitly stated or tested the exact distance threshold on-site, which denotes the limit beyond which workers might not be detected. These limitations point to the need for further research and improvement in our method. Future work should aim to address these issues, as well as incorporate considerations of existing safety measures on construction sites to provide more nuanced safety monitoring information.

6. ACKNOWLEDGEMNT

This research was supported by a grant [2022-MOIS38-002 (RS-2022-ND630021)] from the Ministry of Interior and Safety (MOIS)’s project for the development of accident prevention technology for vulnerable groups. In addition, this research was supported by a grant from the Korean Government (MSIT) to the Research Foundation of Korea (NRF) [RS-2023-00250166] and This work is financially supported by Korea Ministry of Land, Infrastructure and Transport(MOLIT) as 「Innovative Talent Education Program for Smart City.

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DEEP LEARNING BASED POSE ESTIMATION OF SCAFFOLD FALL ACCIDENT SAFETY MONITORING

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ABSTRACT: *According to the Ministry of Manpower, falling and slipping accidents are one of the most common accidents in addition, falls from heights (FFH), including accidents during scaffolding work, are still a major cause of death in the construction industry. Regular safety checks are currently being carried out on construction sites, but scaffold-related accidents continue to occur. Sensing technology is being attempted in many industrial sites for safety monitoring, but there are still limitations in terms of the cost of sensors and object detection, which are limited to certain risks. Therefore, this paper proposes a deep learning-based pose estimation approach to identify the risk of falling during scaffolding work in the construction industry. Through analysis of the correlation between unstable behavior during scaffold work and the angle of keypoints of workers, the proposed approach demonstrates the ability to detect the risk of falling. The proposed approach can prevent falling accidents not only by detecting construction site workers, but also by detecting specific risky behaviors. In addition, in limited work environments other than scaffolding work, the information on unstable behavior can be provided to safety managers who may not be aware of the risk, thus contributing to preventing falling accidents.*

KEYWORDS: *deep learning, pose estimation, keypoint angle calculate, construction site safe monitoring, falls from heights*

1. INTRODUCTION

According to the Ministry of Manpower, falling and slipping accidents are one of the most common accidents in addition, falls from heights (FFH), including accidents during scaffolding work, are still a major cause of death in the construction industry. Working at height on construction sites is associated with a major risk of falls that must be properly managed to prevent injury and death.

Statistics from the U.S. Department of Labor in 2021 indicate that nearly one in five workplace fatalities occurred in the construction industry, with over a third of these attributed to falls, slips, and trips. The construction industry was responsible for 46.2% of all deaths from falls, slips, and trips that year(U.S. BUREAU OF LABOR STATISTICS, 2023).

Based on data from Singapore's construction sector, construction accidents have been on the rise from 2020 to 2022, accounting for 171 incidents (26% of total accidents). Of these, FFH accounted for 55 incidents (32%), while slips and trips were responsible for 27 incidents (15.8%) (MOM, 2022).

Meanwhile, in South Korea, despite the implementation of the Major Accident Act in January 2022 aimed at reducing fatalities among construction workers, there has been a 0.01% increase in such incidents as of March 2023. Specifically, in 2022, out of 539 deaths, 268 were attributed to "falls," marking the highest cause. These statistics reconfirm that the construction sector is hazardous, with a pronounced risk of fall incidents.

While various personal protective equipment and safety devices have been developed to prevent accidents, a study by (Xia et al., 2018) highlighted that one of the main causes of fall incidents is the absence or insufficiency of worker behavior supervision. Information on the posture of construction workers can serve as valuable data for evaluating safety and productivity (Xu et al., 2022). Several studies have been driven based on this perspective.

(Khan et al., 2021) researched methods to detect unsafe behaviors of workers using IMU sensors, specifically by assessing the angle of attached hooks. Enrique (Valero et al., 2016) used wearable devices based on IMU sensors to analyze movement data and detect unsafe postures. There have also been significant strides in using computer

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Seungsoo Lee, Seongwoo Son, Pa Pa Win Aung, Minsoo Park, Seunghee Park, *Deep Learning Based Pose Estimation of Scaffold Fall Accident Safety Monitoring,* pp. 641-647, DOI 10.36253/979-12-215-0289-3.63

vision for safety research. (MassirisFernández et al., 2020) proposed a method to assess work risks by analyzing joint angles of workers under limited visibility conditions.

Deep learning methodologies have also been applied to safety research. (Khan et al., 2021) utilized deep neural networks to classify and segment worker movements, detecting unsafe behaviors on moving platforms. Pinsheng (Duan et al., 2023) introduced a technique using OpenPose to detect personalized stability based on the individual characteristics and habits of workers at height.

However, a gap has been identified in safety monitoring research following the Standard Operating Procedure (SOP). This study aims to address this gap by proposing a method to monitor unsafe postures of workers during scaffolding operations based on their shoulder joint angles, in accordance with the SOP.

Furthermore, by actively incorporating such innovative technology at construction sites, it is possible to enhance worker safety and improve productivity. For instance, these posture detection systems can support workers in maintaining safe working postures and preemptively detect unsafe conditions to prevent accidents. This not only elevates safety standards in the construction industry but also enhances work efficiency while reducing fatigue and injuries during operations.

Moreover, the practical utilization of such technology in construction sites can lead to adherence to project schedules and cost savings. Real-time posture detection and analysis at the site are expected to contribute significantly to enhanced productivity and the creation of a safe working environment in the construction industry.

2. LITERATURE REVIEW

The construction industry has been a focal point of research on workplace safety, largely due to the high frequency of fall-related accidents (MOM, 2022; U.S. BUREAU OF LABOR STATISTICS, 2023). With a significant portion of accidents attributed to falls from heights (FFH), slips, and trips, it is clear that this is an area in need of targeted interventions and technological innovation.

Efforts have been made to mitigate the risk of falls in the construction industry by developing personal protective equipment and safety devices. However, studies suggest that the root cause of fall incidents often lies in inadequate supervision of worker behavior (Xia et al., 2018). Construction worker's postures are a valuable source of stability and productivity information that can be used to manage construction sites (Xu et al., 2022).

Monitoring changes in a worker's posture can provide information about whether the worker is in a safe or unsafe position. Numerous studies have been conducted to detect and analyze unsafe behaviors of workers using this approach. For instance, (Khan et al., 2021) conducted a study using IMU sensors to determine unsafe worker behavior through the angle of secured hooks. Similarly, Enrique (Valero et al., 2016) used wearable devices based on IMU sensors to measure movement data, detecting and characterizing the unsafe postures of workers. Other researchers have also leveraged computer vision to detect and analyze worker posture information. For instance, (MassirisFernández et al., 2020) evaluated job risk by inferring joint angles of workers under limited field of view conditions based on computer vision.

Deep learning has also found its applications in this context. (Khan et al., 2021) identified unsafe behaviors on mobile platforms through object correlation detection using deep neural network-based worker classification and segmentation. Also, (Duan et al., 2023) proposed a personalized stability detection technology based on high-altitude workers' body posture patterns by detecting individual physical characteristics and habits using the OpenPose method.

Amidst these technological advancements in detecting unsafe behaviors, there's a noticeable gap when considering overlapping or closely interacting workers in construction sites. Addressing this complexity, (Park et al., 2023) introduced a method for detecting small and overlapping workers at construction sites, emphasizing the intricate interactions and spatial relations of workers in crowded environments. Demonstrated significant potential in ensuring workplace safety by identifying such challenging scenarios with higher accuracy.

While these prior studies have inferred the results of unsafe worker behaviors using sensors and evaluated worker stability, they often lack in terms of monitoring safety during scaffolding work as per Standard Operating Procedure (SOP). Therefore, this study aims to monitor unsafe postures by detecting shoulder joint angles of workers during scaffolding work based on SOP, as an effort to prevent fall accidents in this context.

3. METHODS

3.1 Research framework

In the construction industry, the safety of workers holds paramount importance, especially with the rising concerns related to fall-related accidents. Traditional methodologies have primarily leaned towards sensor-based approaches to address these concerns. However, there's a growing interest in methodologies based on computer vision. In this framework, we utilize the YOLOv7 Pose algorithm to detect and assess the shoulder joint angles of construction workers to discern potential hazardous situations. As illustrated in Fig. 1 the framework to monitor the stability of construction workers working at elevated heights consists of five modules. First, data is collected from the construction site, encompassing a myriad of movements by the workers. From the collected video data, essential frames are extracted and major regions pertaining to the workers are labeled accordingly. Next, the YOLOv7 Pose algorithm is employed to detect the skeleton of the workers. Special emphasis is laid on the skeleton information around the shoulder joint to calculate the angle of the shoulder joint. Subsequently, an analysis is performed to determine if the current angle of the worker's shoulder joint poses any risk in comparison to a set standard angle. If any hazardous posture is detected, real-time alerts are displayed, urging the implementation of necessary safety measures.

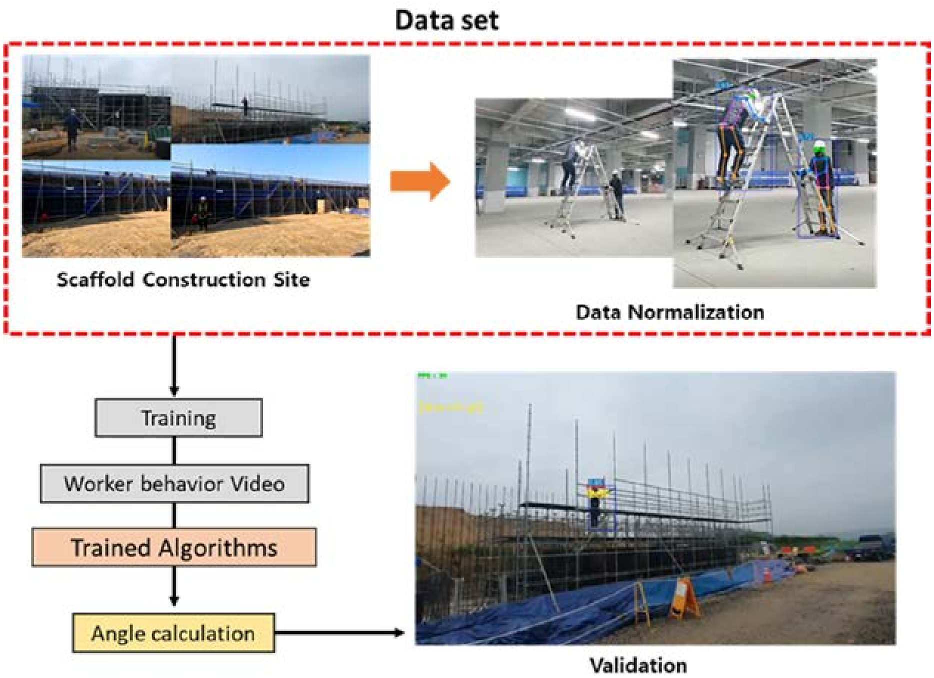

Fig. 1: Research Framework.

3.2 Identification method

Ensuring the safety of construction workers in high-risk environments, such as working at heights, has always been a top priority in the construction industry. Falls from heights are a common type of accident on construction sites, and many of these incidents occur when workers lose their balance and become unstable. In particular, scaffold work, which is frequently performed by construction workers, is associated with a high number of accidents. Therefore, in this study, the OpenPose method, which detects human postures from images and videos, was used to detect and analyze the postures and joint information of scaffold workers. The algorithm, trained using the MS COCO dataset and videos captured at construction sites, detects and represents human posture as shown in Fig. 2 It identifies a total of 17 joints, numbered from 0 to 16, as illustrated in Fig. 2, right image, and provides information about each joint. Table 1 illustrates unsafe postures that can occur during scaffold work. While various postures are possible during scaffold work, such as sitting, standing, bending, or bowing the head, there is a posture where both arms are raised simultaneously, lifting both the left and right shoulders, with a shoulder angle of less than 90 degrees. In this study, a posture involving the simultaneous elevation of both arms and shoulders with an angle less than 90 degrees is designated as an unsafe posture.

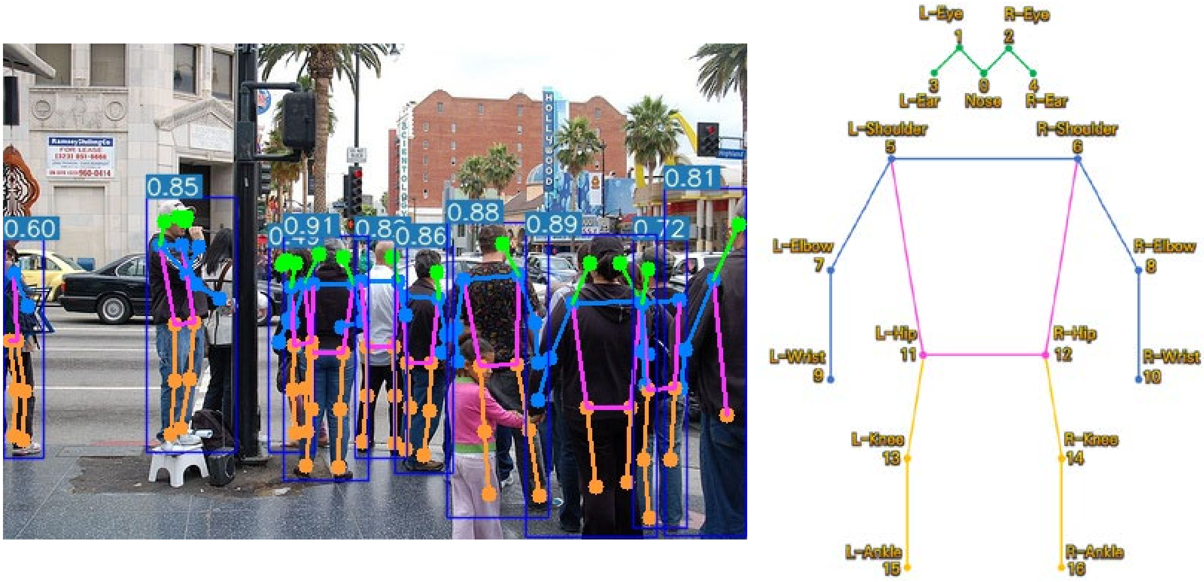

Fig. 2: Joint position information.

Table 1: Unstable behavior criteria for scaffolding operations

Unstable behavior description	Angle name	Angle numbers	Range	Threshold
Arm rasing	Left-Shoulder	∠7,5,6	0°~270°	∠LS ≤ 90°
	Right-Shoulder	∠8,6,5	0°~270°	∠RS ≤ 90°

3.3 Feature extraction

Algorithm 1 demonstrates a method for representing risk alerts based on angle calculations. This is employed to indicate stability alerts based on the angle when a worker raises their arm during operations. The algorithm consistently computes risk alerts based on shoulder angles, thereby continuously detecting workers and providing real-time notifications for risks associated with unsafe postures. It processes the input, detecting individuals in the video, and then delineates Bounding Boxes (BBox) and keypoints. Subsequently, it performs ongoing calculations for the angles of the R (Right) and L (Left) Elbows and R, L Shoulders. When the angle falls between 90 and 180 degrees, a warning notification is sent, while angles below 90 degrees trigger an Unsafe posture notification, which is visualized and transmitted.

Algorithm 1: Finding Angle between Three Points

Input: Detected Workers

Output: angle

```
Extract coordinates for p1, p2, p3 from kpts.
Calculate angle using atan2.
if angle >= 180.0 THEN label = '[safe!]', color = blue
else if 90 < angle < 180 THEN label = '[Warning!]', color = yellow
else label = '[Unsafe!]', color = red
if draw then visualize angle, label on image.
Return angle.
```

Fig. 3 demonstrates the method for detecting unsafe postures when the algorithm is applied during video recording. The YOLOv7 algorithm was utilized for its speed and capability to detect individuals while simultaneously detecting joints. The worker's joints are divided into 17 distinct points, from the head to the legs, each assigned an ID. To identify unsafe postures during scaffold work, the angles of the shoulders are crucial when the arms are raised. Therefore, angles for the joints L-Shoulder(5) and R-Shoulder(6) were detected and calculated. For angle calculation, a line connecting L-Shoulder(5) and R-Shoulder(6) was used as the baseline, and vectors were applied to the Elbow joint for angle calculation, as the calculation required angles for external rotation at each shoulder joint. Following the KOSHA GUIDELINE, when a worker raises their arm, an unsafe posture is determined based on a 90-degree threshold. The system alerts the user with three levels: over 180 degrees for safe, between 90 and 180 degrees for warning, and below 90 degrees for unsafe.

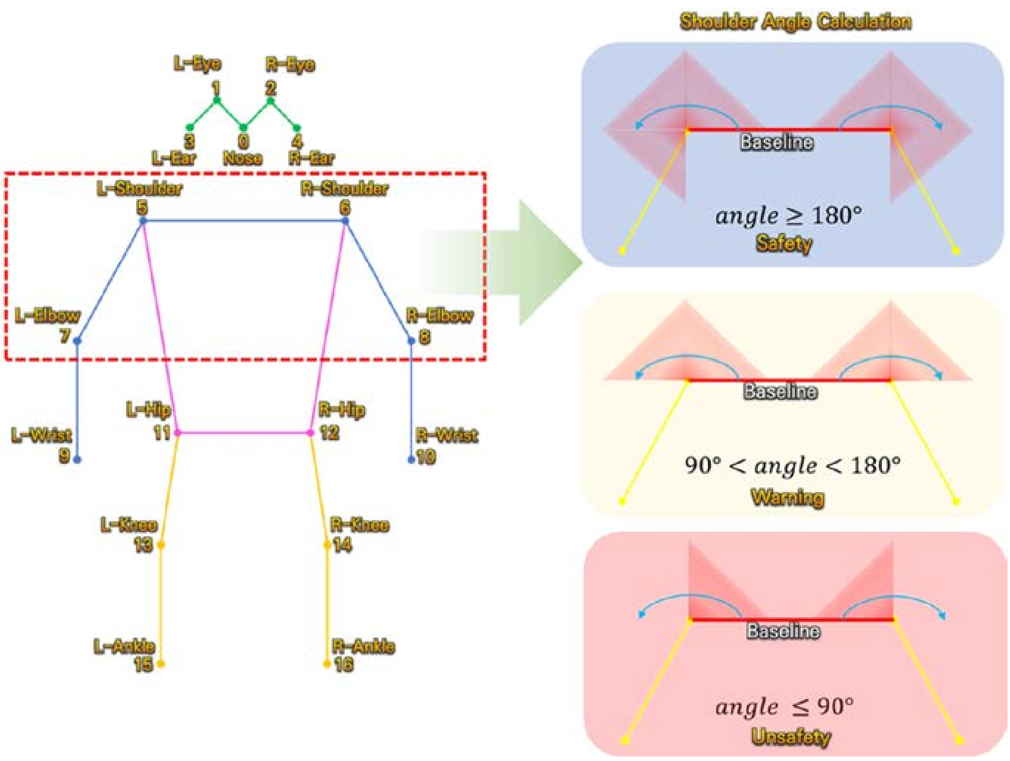

Fig. 3: Joint information and how to calculate shoulder joints

4. RESULTS

(a)

(b)

Fig. 4: Worker safety monitoring results during scaffolding operation. (a) Scaffolding installation work image taken diagonally, (b) Scaffolding installation site work image taken from the front

In Fig. 4 (a) presents the results of detecting a worker engaged in scaffold installation captured from a diagonal angle. When the worker raises their arms, the proposed angle-based criteria triggers a [Warning!] alert, indicating the detection of the worker and the activation of the alarm system. In (b), an image captured from the front showcases the construction site, not only identifying scaffold workers but also other workers engaged in different processes. As these workers are not in the arm-raised posture, no warning alerts are generated.

The proposed method for detecting unsafe postures during elevated work involves worker detection on construction sites and shoulder joint angle assessment for safety monitoring. This approach aligns with safety posture guidelines applied when workers raise their arms during elevated tasks, providing real-time warning notifications. This experiment validates the robustness of this study in facilitating easier site supervision and monitoring by administrators in complex and chaotic construction environments.

5. CONCLUSION

This study aims to contribute to the advancement of automated safety monitoring technology in the field of construction sites. The proposed method utilizes a Deep Learning-based OPENPOSE pose estimation model to estimate the postures of scaffold workers on construction sites. This estimation aims to provide real-time risk alerts to prevent falls from height (FFH) accidents. This research is expected to reduce the fatigue of construction site managers and decrease the occurrence rate of scaffold-related fall accidents.

However, during this research, limitations and areas for improvement have been identified. Due to the nature of construction sites, there are often obstacles and situations where workers are obstructed or difficult to detect due to equipment. Additionally, as objects move farther from the camera, issues were observed in joint angle calculations and false positives/negatives of worker detection. This indicates the need for further research and algorithm improvements. To address these challenges, future research aims to enhance detection accuracy based on distance and devise strategies to detect workers obstructed by obstacles. Furthermore, incorporating Multi-Camera setups is intended to calculate worker head angles.

6. ACKNOWLEDGEMENT

This research was supported by a grant from the Korean Government (MSIT) to the Research Foundation of Korea (NRF) [RS-2023-00250166]. In addition, this research was supported by a grant [2022-MOIS38-002 (RS-2022-ND630021)] from the Ministry of Interior and Safety (MOIS)'s project for the development of accident prevention technology for vulnerable groups. National Research Foundation of Korea (NRF) through the Ministry of Science and ICT (MSIT), Korea Government, under Grant [NRF-2021R1A4A3033128]. This work is financially supported by Korea Ministry of Land, Infrastructure and Transport(MOLIT) as 「Innovative Talent Education Program for Smart City」.

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PREDICTIVE SAFETY MONITORING FOR LIFTING OPERATIONS WITH VISION-BASED CRANE-WORKER CONFLICT PREDICTION

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ABSTRACT: *Construction industry has reported among the highest accident and fatality rates over the past decade. In particular, crane lifting is a notably hazardous operation on construction sites, causing fatal accidents like workers being struck by the boom or objects fallen from tower cranes. Manual monitoring by on-site safety officers is labour-intensive and error-prone, while incorporating computer vision techniques into surveillance cameras would enable more automatic and continuous monitoring of construction site operations. However, existing studies for lifting safety mainly detect the presence of individual objects (e.g. workers, crane components), while a methodology is needed to predict their potential collision more proactively before accidents happen. This paper develops a vision-based framework for predictive lifting safety monitoring, including three modules: (1) object detection and classification: targeting at hook and lifting materials to enable danger zone estimation, along with workers and their personal protective equipment; (2) worker movement tracking and prediction: analyzing the historical moving trajectory of each unique worker to foresee his/her future movement in certain period ahead; (3) multi-level safety assessment: issuing predictive warning in real-time upon any crane-worker conflict foreseen. The proposed framework is applicable to real-time site video processing and enables end-to-end lifting safety monitoring with instant alerting upon unsafe scenarios observed. Importantly, the proposed framework predicts the future movement of workers to proactively identify potential site hazard, in order to trigger earlier safety alert for more timely decision-making. With a large video dataset capturing tower crane operations, the proposed framework demonstrates competitive accuracy and computational efficiency in crane-worker conflict prediction, validating its practicality for real-time lifting safety monitoring.*

KEYWORDS*: Computer Vision; Construction Safety Monitoring; Crane-Worker Conflict Prediction; Deep Learning; Predictive Safety Assessment; Trajectory Tracking.*

1. INTRODUCTION

The construction industry has been plagued for long by a high frequency of accidents and fatalities. According to statistics from the Hong Kong Labour Department (2018), the industry accounted for 76% of occupational fatalities in 2017, making it the most dangerous sector in Hong Kong. Similarly, the U.S. Bureau of Labour Statistics (2018) reported an average rate of 2.6 deaths per day, resulting in 949 deaths for the year. With reference to an overview of the Hong Kong construction industry (Shafique & Rafiq, 2019), there were on average 3597 occupational injuries and 20 occupational fatalities per year between 2011 and 2017. The U.S.A Department of Labour (2022) indicated that the estimated cost of employers' direct compensation to construction accidents is up to US$1 billion per week. These statistics suggest the urgent need for improved construction safety measures to protect the lives of workers and mitigate the financial burden that accidents impose on employers and the economy.

To address this critical issue, governments have established safety guidelines and regulations to standardize the industrial practices of construction safety monitoring. Lifting operations using tower cranes are a crucial aspect of construction work that requires particular attention, as they involve dynamic interactions between workers and machines. Traditionally, safety monitoring relies heavily on manual inspection by on-site safety officers. However, this method is prone to errors due to human fatigue, which can result in overlooked incidents. In recent years, advancements in artificial intelligence have led to the development of computer vision (CV) methods that can automate construction safety monitoring. These methods enable real-time object identification, improving the accuracy and efficiency of safety monitoring. However, there are two research gaps: (1) Previous approaches have focused on analyzing individual objects, such as workers and machines, separately, without a more comprehensive framework that considers their spatial interaction in real-time. (2) Previous studies have primarily focused on analyzing current scenarios/activities on sites, while a more predictive mechanism is needed to proactively identify and prevent potential accidents ahead of time. Therefore, this study develops a predictive safety assessment framework that monitors potential crane-worker conflicts and enable proactive incident prevention, ultimately reducing the number of accidents and fatalities in the construction industry.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Peter Kok-Yiu Wong, Synge C. P. Lam, Isabel Y. N. Lee, Felix C. L. Ting, Jack C. P. Cheng, Pak Him Leung, *Predictive Safety Monitoring for Lifting Operations with Vision-Based Crane-Worker Conflict Prediction,* pp. 648-656, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.64

2. RELATED WORK

Collision between workers and construction equipment happens regularly in complex and distracting construction environment that is overcrowded with workers. Close contact between construction machines and workers are one of the major causes of collision event that lead to injuries and deaths. Sensors such as GPS and RFID have been explored in prior studies. With the help of sensors, real-time spatial-temporal information could be provided for proximity measurements. As a result, a spatial-temporal relationship can be detected, and an early warning can be sent out to prevent the accident from happening (Liu et al., 2021). However, to obtain enough information to safeguard the construction site, numerous sensors have to be installed. The heavy financial burden will be caused by purchasing and hiring a professional individual to install and maintain the sensors (Zhang et al., 2020).

CV-based object tracking is a superior alternative to sensors since it lowers the cost and requires fewer resources to set up, therefore, more appealing to the industry. Previous research has trained YOLOv3 deep learning model for 2D positioning various construction site entities on 2D images captured from Aerial vehicles. Several studies developed convolutional neural networks to detect personal protective equipment (PPE), such as helmet and reflective vest (Cheng et al., 2022, Fang et al. 2018, Nath et al. 2020). Besides object detection, several studies developed human tracking algorithms to analyze behavior of each person more continuously (Kim et al., 2019, Wong et al., 2021). Other studies attempted to predict the future action of construction machines like excavators, based on their historical motion patterns (Luo et al., 2021), and also semantic segmentation that fine-grains the detected objects at pixel level to allow better positioning (Jeelani et al., 2021).

While previous studies can perform real-time object detection and tracking, a more comprehensive framework beyond developing those algorithms is needed for practical construction safety monitoring. An automatic safety evaluation system shall be established to enable effective intervention mechanisms to prevent the accident from happening. Previous studies have proposed some distance-based hazard evaluation criteria (Son et al., 2019). Some researchers have taken the velocity of construction equipment and workers into consideration as there is an association between larger velocity and collision accidents (Golovina et al., 2016). A previous study has attempted to determine the dynamics direct fall zone of a crane load using a mounted tower crane camera with computer vision (Chian et al., 2022). These studies enhance construction safety monitoring with the ability to predict the direct fall zone, where workers can be proactively prevented from entering danger zones.

3. PROPOSED METHODOLOGY

To facilitate tower crane safety monitoring, a vision-based framework is developed which comprehensively supports end-to-end CCTV analytics for real-time safety assessment. The overall procedure and information flow are summarised in **Figure 1**, with three major functional modules: (1) **object detection and classification**: interested objects in each video frame are detected and classified into three categories (i.e. workers, hook and lifting materials); (2) **worker movement tracking and prediction**: analyzing the historical moving trajectory of each unique worker and predict his/her possible location in certain period ahead; (3) **multi-level safety assessment**: issuing predictive warning in real-time upon any unsafe crane-worker conflict observed.

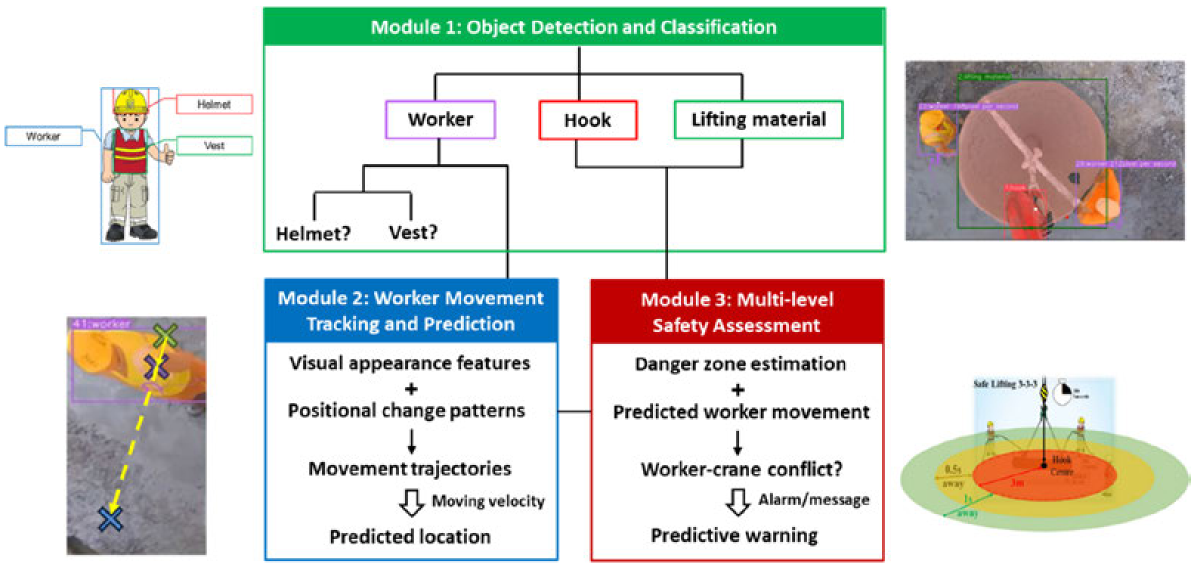

Figure 1: Overall information flow of the proposed crane safety monitoring framework

3.1 Object detection and classification

Upon receiving the raw videos from multiple cameras, the objects of interest are identified in Step 1. This is a crucial step that demands an automated process and accurately bounded objects (i.e. cropping the portion of image around each object with minimal background clutter). There have been numerous studies specialized in construction object detection (Fang et al., 2018; Luo et al., 2019; Memarzadeh et al., 2013), as well as comprehensive surveys of various state-of-the-art object detection methods (Brunetti et al., 2018; Huang et al., 2017). Hence, this paper adopts a competitive detection model for the object detection step. In particular, the YOLOv8 algorithm is used in view of its detection accuracy and inference efficiency revealed in recent studies.

More specifically, three types of construction objects are targeted, i.e. construction workers, crane hook and lifting materials during crane operations. With videos collected from construction sites, each object-of-interest is detected and cropped as a rectangular bounding box. Subsequently, a classification module outputs the corresponding class index associated with each bounding box. **Figure 2** illustrates a sample output of detection and classification (worker bounded by a purple box, hook by red and lifting material by green).

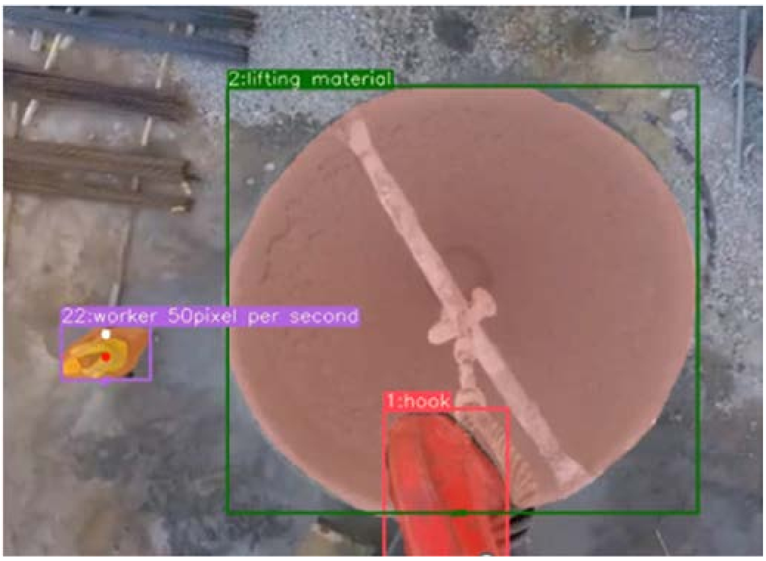

Figure 2: Illustration of object detection and classification results

For those detected boxes labeled as workers, a more fine-grained classification regime is defined to further analyze whether each worker wears necessary PPE, i.e. helmet and vest. As illustrated in **Figure 3**, two sub-categories are output by the classification model to determine the presence of helmet and vest respectively in their corresponding part of a body. To make the methodology more practical, the model is trained with both confirming and dis-confirming classes, e.g. the head part is marked even no helmet exists around there. This approach renders the PPE inspection more accurate, because it avoids improper behavior, e.g. hand-carrying a helmet without properly wearing on the head. In that case, our method can correctly report that PPE is not properly worn, while ordinary detection method only identifies the presence of PPE in hand, which indeed violates PPE compliance.

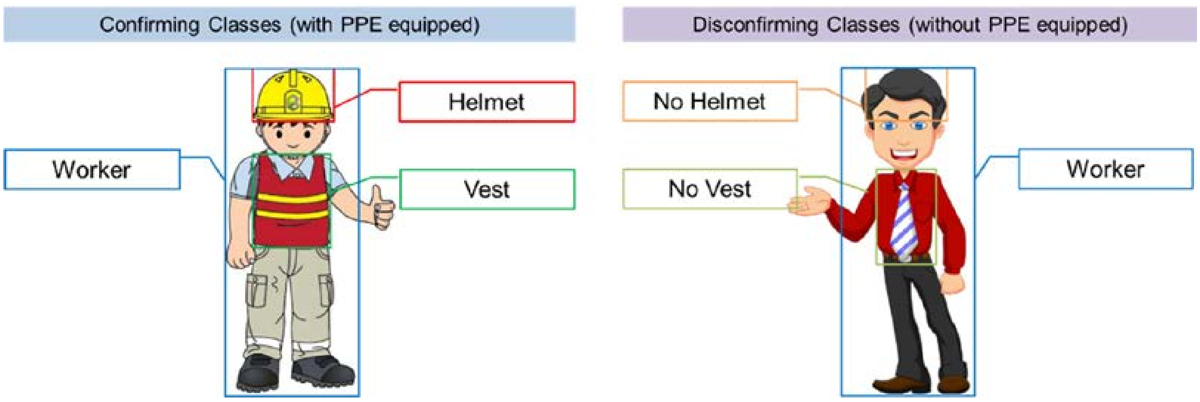

Figure 3: Definition of PPE statuses of a worker

3.2 Worker movement tracking and prediction

On top of the object detection results, worker trajectory tracking is performed to support worker behavioral analysis based on movement pattern. In this study, the method DeepSORT (Wojke et al., 2017) is utilized as a baseline to perform worker trajectory tracking over video frames, acquiring a complete trajectory of individual construction worker. The set of bounding boxes classified as ‘worker’ in Step 1 are further processed by DeepSORT, which subsequently analyzes the appearance features extracted from each worker and the positional change of the bounding boxes, in order to map unique identities to individual worker. **Figure 4** illustrates the assignment of unique identities to individual workers (22 to the left-sided worker, 29 to the right one).

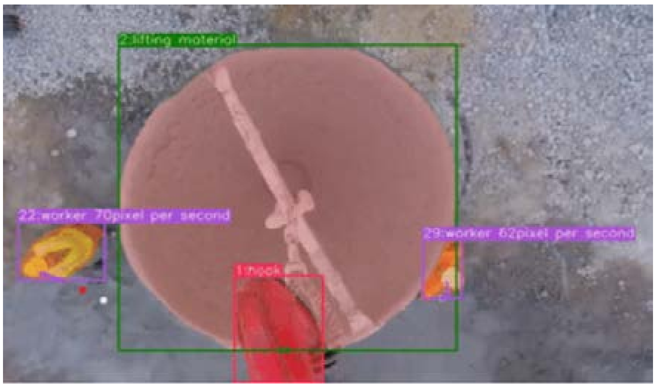

Figure 4: Illustration of worker tracking with unique identity assigned to different workers

Based on the trajectories of individual construction workers, their potential movement is then predict to foreseen whether their moving trajectories will potentially coincide with any lifting zone of the tower cranes nearby. This will allow dispatching warning signals in a more timely manner before workers actually enter the lifting zones. The prediction of future movement of each worker is defined in **Equation (1)**, which computes the image coordinates of the predicted worker location *t* timesteps later based on his/her observed velocity *v*.

$$d_2 = d_1 + v \times t \quad \textbf{(1)}$$

where,
d_1 = coordinates of the current location,
d_2 = coordinates of the predicted location,
v = velocity along corresponding direction,
t = time (measured by number of frames).

3.3 Multi-level safety assessment

By combining the output from object detection and worker movement tracking modules, spatial relationship between construction workers and lifting equipment is established. Regarding tower crane operations, the “Safe Lifting 3-3-3” Principle published by Hong Kong government (2020) is an industry standard in lifting operations. As illustrated in **Figure 5**, the 3-3-3 Principle states that workers should keep themselves 3m away from the lifting materials to ensure their safety. Yet, the 3-3-3 Principle only defines a single level of safety distance to be maintained from the lifting zone, while different degree of proximity may imply various levels of safety. Moreover, the standard only considers static behavior of workers (i.e. current location), while a more predictive safety monitoring regime is needed to consider the possible movement of each worker in certain period ahead.

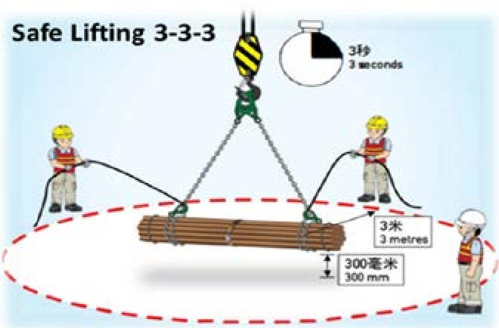

Figure 5: Definition of Safe Lifting 3-3-3 Principles

On top of the 3-3-3 Principle, the 3m operating region is defined as the danger zone around the lifting material detected by the object detection module. With the bounding box of lifting material generated, a danger zone of radius 3m around the bounding box centre is estimated. Different warning signals are then sent according to the corresponding risk scenarios and the predicted trajectory of the workers. As summarized in **Table 1**, different scenarios implies corresponding level of response. If a worker is already inside a fatal zone, 'Action' is issued to urge for immediate handling. If he/she is predicted to enter a fatal zone in 3 or 5 seconds, the responses become 'Alarm' and 'Alert' respectively which are less severe. Such a multi-level warning mechanism enables more flexible and predictive safety assessment.

Table 1: Proposed three-level mechanism of lifting safety assessment

Response	Scenario
Action	Worker inside fatal zone
Alarm	Worker will enter fatal zone in 3 seconds
Alert	Worker will enter fatal zone in 5 seconds

To alert both the workers and the residential site safety personnel to the potential safety hazards, an instant warning system is developed with a series of if-else loops, and connected with an external chatbot API. When the model detects the worker's tendency to enter the defined lifting zone, warning messages are issued to inform safety officers of the incident detected. The corresponding frames is also captured, with descriptive text about the unsafe scenario, and sent to registered stakeholders via an instant messaging platform (e.g. Telegram) for remedial actions.

4. EXPERIMENT

4.1 Experimental setup

To prepare a rich dataset for validation, CCTV videos taken in different angles were collected, including those taken by at-grade cameras and mounted-on-crane cameras. **Table 2** summarizes the attributes and sources of the videos solicited, which can be referred to in future studies for tower crane safety monitoring.

Table 2: Statistics of the image dataset collected for model evaluation

Angle	Length	Types	Sources
At-grade	2 min 50 sec	PPE wearing	https://youtu.be/zmVjnWEX_5c
At-grade	24 min 36 sec	Crane operations	https://youtu.be/Ag5yV8qZKMQ
At-grade	15 min 56 sec	Worker behavior	https://youtu.be/3AbhT6TLf60
Top-down	3 min	Crane operations	https://youtu.be/IlaEJgq0aEw
Top-down	4 min 18 sec	Crane operations	https://youtu.be/Vg6SOcPviDs
Top-down	4 min 35 sec	Crane operations	https://youtu.be/lrhQHX3r-pM
Top-down	59 sec	Crane operations	https://youtu.be/viBcyF2H_1A

A total of 5575 images were generated by extracting frames out of the collected videos, with manual inspection and sampling of high-quality frames, i.e. capturing diverse details of worker / crane operations. A detailed statistics of the dataset generated is summarized in **Table 3**.

Table 3: Statistics of the image dataset collected for model evaluation

Set	No. of images
Training	4889
Validation	458
Testing	228
Total	5575

The collected data then underwent a series of augmentations to maximize the generalization capability of the model being trained. The types of pre-processing include image resizing, rotation by EXIF orientation values and grayscale conversion. The images were also augmented by horizontal and vertical flipping, hue and saturation adjustment. Afterwards, the dataset was split into training, validation and testing sets. The training set was fed into different variants of object detection models, including YOLOv8-Large, YOLOv8-Small and YOLOv8-Nano, which consist of different degrees of model complexity in terms of neural network architecture.

As summarized in **Equations (2)-(4)**, the evaluation metrics of for object detection and classification include recall, precision and average precision (AP) score. Moreover, the accuracy of worker trajectory tracking is evaluated by multi-object tracking accuracy (MOTA), as defined in **Equation (5)**, where $IDSW$ denotes the frequency of identity switching among workers detected. In addition, the computational speed of the proposed method is also evaluated (in frame-per-second), which validates the practicality of our framework in real-time CCTV processing for construction site monitoring.

$$Recall = \frac{TP}{TP + FN} \tag{2}$$

$$Precision = \frac{TP}{TP \ + FP} \tag{3}$$

$$AP\ score = \frac{TP + TN}{TP \ + FP + TN + FN} \tag{4}$$

$$MOTA = 1 - \frac{FN + FP + IDSW}{TP + TN} \tag{5}$$

4.2 Results and discussion

Table 4 summarizes the AP scores of the object detection module of the proposed framework. Overall, a mean AP of 97.0% is achieved among all the three object classes, with 99.5% AP score for both the classes 'hook' and 'material'. A slightly lower AP score of 92.0% is obtained for 'worker', because of the significant variation of worker sizes in the images, which capture both top-down and at-grade angles from largely varying distances.

Table 4: Evaluation results of object detection

	Class	**AP score**
Class-wise	Worker	92.0%
	Crane hook	99.5%
	Lifting materials	99.5%
Overall	Recall	98.0%
	Precision	96.0%
	Mean AP	97.0%

Table 5 summarizes the AP scores of the worker PPE classification module of the proposed framework. Overall, the mean AP improves from 96.9% to 99.5% when training the PPE classification module with both confirming and dis-confirming cases. Such an approach also boosts the class-wise AP scores, from 96.7% to 99.3% ('helmet') and from 97.0% to 99.5% ('vest'). The effect of incorporating the dis-confirming cases is that the classification model has learnt more distinctive features of those PPE from the negative samples. For instance, by seeing ordinary cloths without vest, the model intrinsically learns better how a vest should look like and hence more accurately classifies whether a person is properly wearing a vest.

Table 5: Evaluation results of worker PPE classification

		Case 1 – trained with confirming classes only	**Case 2 – trained with confirming & dis-confirming classes**
Class-wise AP scores	Helmet	96.7%	99.3% ↑
	No helmet	/	99.2%
	Vest	97.0%	99.5% ↑
	No vest	/	99.6%
Overall scores	Recall	96.9%	98.8% ↑
	Precision	97.1%	98.8% ↑
	Mean AP	96.9%	99.5% ↑

Table 6 summarizes the MOTA (for worker tracking) and computational speeds when combining DeepSORT with different YOLOv8 variants. Regarding worker tracking accuracy, YOLOv8-Large outperforms the other two models with the highest MOTA of 90.1%, while having slower computational speed than the other two (2.7 frames per second). YOLOv8n-Nano shows the fastest inferencing (13.4 frames per second), while its MOTA is 81.8% which may be due to the increased chance of missing detections. Hence, YOLOv8-Small achieves the most balanced performance (85.2% MOTA and 7.9 frames per second).

Table 6: Evaluation results of worker trajectory tracking and overall computational speed

Model variant	MOTA	Computational speed (frame-per-second)
YOLOv8-Large+DeepSORT	90.1%	2.7
YOLOv8-Small+DeepSORT	85.2%	7.9
YOLOv8-Nano+DeepSORT	81.8%	13.4

Figure 6 illustrates the predictive warning mechanism of the proposed framework. The developed modules process a complete video and identifies that construction workers are working within the danger zone during lifting operations. By detecting the location of the lifting equipment and tracking the movement of individual construction workers, warning signals and recommended actions are dispatched via a Telegram chatbot upon identifying the unsafe scenarios. The spatial relationship among the equipment and workers is accurately established, which then informs on-site safety managers of the workers' risk statuses, urging for immediate actions more timely. Hence, our proposed framework enables more predictive safety monitoring of crane operations.

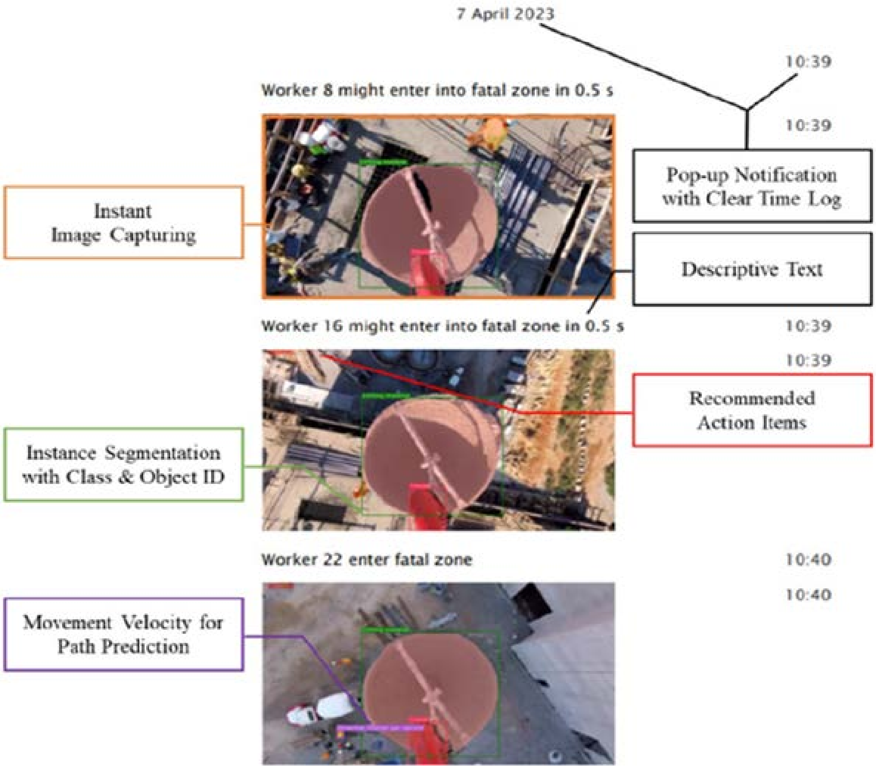

Figure 6: Demonstration of predictive warning mechanism in video processing

5. CONCLUSION AND FUTURE WORK

This paper proposes a vision-based framework for predictive lifting safety monitoring, relieving the tedious and error-prone manual inspection on sites in traditional practices. By analyzing the spatial interaction among essential objects in lifting operations (e.g. predicted movement of workers, danger zone around hook and lifting materials) more predictive incident identification is enabled for timely on-site safety assessment. The competitive accuracy and computational efficiency demonstrated in this study validates the practicality of the proposed framework. Based on the experimental findings, two research directions are suggested for future research: (1) **camera placement optimization in actual deployment**, considering various factors such as view coverage, degree of object occlusion, view angle and distance (implying video quality and hence analytical accuracy), etc. Research effort may be devoted into quantifying these factors into optimization framework formulated for camera placement, including the number of cameras, their position and orientation, etc.; (2) **multi-modal sensor integration**, extending the vision-based methodology to analyze more worker behavior such as injury/fall detection, and possibly also incorporating other kinds of sensors such as temperature sensor for heat-stroke warning monitoring and proximity sensor for worker-equipment conflict. More comprehensive research in the future will contribute to forming a systematic approach for construction safety monitoring.

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LOCALIZING AND VISUALIZING THE DEGREE OF PEOPLE CROWDING WITH AN OMNIDIRECTIONAL CAMERA BY DIFFERENT TIMES

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ABSTRACT: *The Corona Disaster increased the demand for information on the degree of human crowding, as it was essential to balance avoiding restricting behavior and reducing the risk of crowding. Although there are many technologies for detecting people using monitoring cameras, the number of cameras installed in a wide area is costly, and coverage is limited. In this study, we propose a method to qualitatively visualize the distribution of people by using images captured by a moving omnidirectional camera from the viewpoint of facility management during regular security patrols. Omnidirectional images are used for both 3D modeling of the target space based on SfM* (*structure from motion*) *and person detection/tracking by machine learning. The distribution of people is visualized qualitatively by obtaining the positions of the extracted people on the 3D model of the site and mapping them. The parallel software processing of visitor observation and mapping is expected to be highly cost-effective in terms of implementation and operation. On the other hand, although there are time deviations in the mapping depending on the location, the visualization and the updated time show their usefulness in understanding the distribution of congestion.*

KEYWORDS: *COVID-19, people's congestion, omnidirectional camera, SfM (Structure from Motion), machine-learning*

1. INTRODUCTION

1.1 Research background

COVID-19 infection was moved to category five infectious disease in Japan on May 8, 2023. The wearing of masks has been left to the discretion of individuals and businesses, and the condition is coming to an end. During the coronavirus outbreak, infection control measures such as wearing masks, hand sanitizers, and refraining from going to places with a high risk of becoming infected became widespread at the individual level and effectively controlled other infectious diseases. However, with the relaxation of waterfront measures and the increase in the number of foreign tourists, there is a risk that other contagious diseases may be brought into Japan, and the number of older people at high risk of serious illness is expected to increase due to the aging of society. As shown in Fig. 1, the number of influenza cases reported from medical institutions (fixed points) nationwide in 2023 showed an increasing trend, with many weeks exceeding the average number of cases reported over the previous five years (National Institute of Infectious Diseases, 2023).

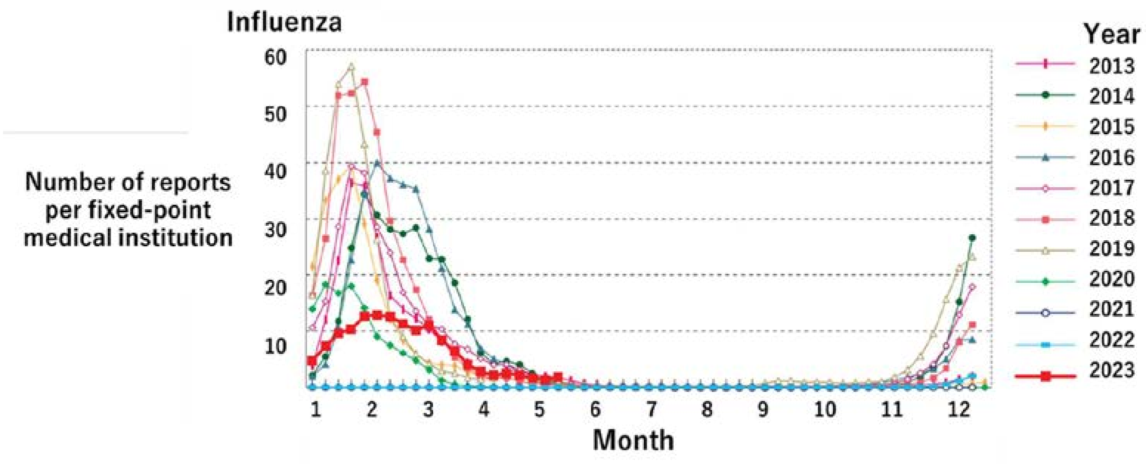

Fig. 1: Number of Influenza Infections
(National Institute of Infectious Diseases, 2023, partially modified and translated)

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Therefore, in the after-coronas, it is necessary to continue infection control measures for individuals such as the older generations and people with underlying medical conditions who are at high risk of serious illness.

On the other hand, consumers are restricted in their purchasing behavior by spatial interference and competition among customers in a retail environment with high customer density within a store. As a result, it has been confirmed that consumers' purchasing decisions are negatively affected, resulting in lower satisfaction (Eroglu et al., 2005). Therefore, in terms of large-scale facility management, a system to ensure social distance is still essential in tourist attractions, commercial facilities, and other places where many people usually gather, and there is a high demand for being able to check the level of congestion in an environment where people tend to gather before visiting.

1.2 Previous work

An example of a familiar means for consumers to obtain local congestion information in advance is the "Congestion Radar" published on the web by Yahoo! (Yahoo! JAPAN,2023). Fig. 2 shows an example of the "Congestion Radar" display of congestion in the vicinity of Tokyo Station (Japan). The "Congestion Radar" visualizes the degree of congestion on a heat-map-like color-coded map of Yahoo! Japan by generating statistics of user location information based on the usage of applications provided by Yahoo! As shown in Fig. 3, EXPOCITY (Japan), a large-scale commercial facility, uses existing technology to visualize the traffic volume aggregated by sensors that detect intrusion and passage in a color-coded format, allowing users to view parking lot congestion on the official homepage. These are all abstract and have the disadvantage that it is difficult to confirm the state of each part of a commercial facility and the distribution of individual people, making it difficult to visualize the state of congestion. In addition, many technologies detect and visualize people using monitor cameras inside facilities (Hitachi, Ltd, 2020, for example). However, since it is necessary to install multiple cameras in a wide area to check and compare the field of view individually, the operation of existing monitor cameras is costly in terms of the number of cameras installed, and there are also limitations in terms of the stability and comprehensiveness of the images. As a study to visualize human distribution from monocular wide-field images, the authors have conducted 3D modeling of the target space based on SfM (Structure from Motion) and human detection and tracking processing by machine learning from images captured by a 360 deg camera and mapped them onto a 3D model of the site and demonstrated its effectiveness in principle (Muraoka et al., 2022). However, this method has drawbacks in systemization regarding scalability and continuous operation since the 3D data of each site is regenerated each time it is photographed to update the information on the distribution of people. In addition, because the people's distribution is visualized on the 3D model of the site, it was not easy to grab the surrounding location relationships and thus limits readability for users as a map.

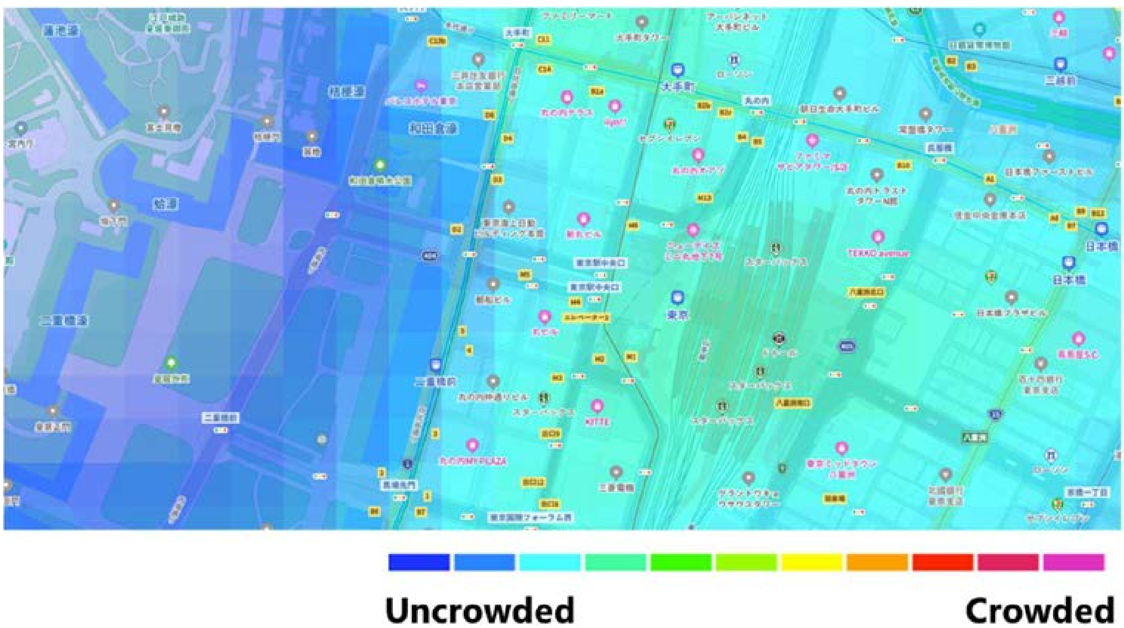

Fig. 2: Example of congestion radar on a map
(Yahoo! JAPAN , 2023, partially modified)

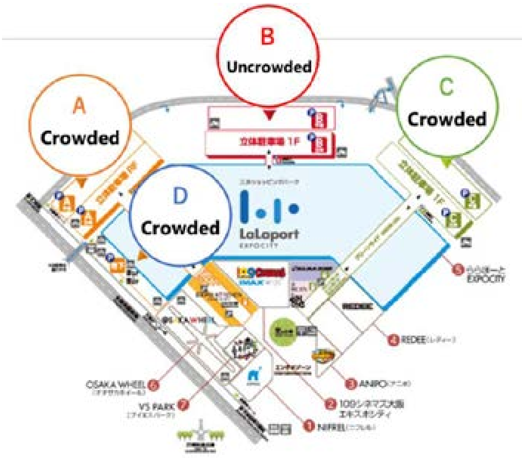

Fig. 3: Example showing parking congestion
(EXPOCITY,2023, partially modified)

2. PROPOSED METHOD

2.1 Outline of the proposed method

To solve the above problem, this study proposes a method of displaying and updating congestion information on a floor map, as shown in Fig. 4, by moving around while taking pictures with an omnidirectional camera carried by security guards or regular base patrol officers in large commercial premises where people move in and out relatively frequently. Fig. 5 shows the processing steps of the proposed method. First, an omnidirectional camera captures images of the surroundings while moving around the target site. Using the photos from the video frames as input for the SfM process, which performs 3D reconstruction of the target scene, and a 3D coordinate system is constructed. As shown in Fig. 6, the captured video is processed for large-scale sites by dividing it into multiple areas. SfM is performed for each area to generate a 3D reconstruction and coordinate system. The video is zenith-corrected so that the vertical axis direction of the image is aligned with the vertical direction of the SfM model. Next, a coordinate transformation equation from the SfM model coordinates to the image coordinates of the floor map image of the facility is calculated by solving a point set matching problem, and the positional relationship between the SfM model and floor map for each patrol position is mapped as shown in Fig. 7. The above process is the preliminary processing performed only at the beginning.

In the person placement process, the same zenith correction processing as above is performed on video frames taken by security guards and others during their patrol duties, and the video data is stored in the cloud service. The video frames are used as input for person detection and tracking. Fig. 8 shows a person detection and tracking process for a video image V taken at a particular location. A specific detector detects multiple targets to be tracked in each video frame, and the same ID is assigned to the same target tracked from frame to frame. In a group of images obtained at regular intervals from video frames (Frame t in Fig. 8), the information on the same person in the frames is integrated to determine whether the object detected as a person in each image is new. If the person is newly detected, the image in which the person is detected is added to the set of input images for SfM. When SfM is executed again, the coordinate system that has already been generated is maintained, and the information of the added image is processed incrementally to calculate the coordinates of the shooting position of the new image. Then, the coordinates of the feet of the new person in the image are obtained, and the person's position in the SfM model is calculated based on the relationship with the camera coordinates. In this way, the distribution of persons can be additionally and successively updated in a consistent coordinate system.

The position of a person on the floor map is calculated by transforming the coordinates from the previously calculated SfM coordinates to the floor map image, and a symbol of the person's size is placed. The symbols on the floor map are then deleted each time data captured by the omnidirectional camera is input, and the map displaying the distribution of people is updated at each time based on the input timestamps. Even over a wide area, the map can be updated piecemeal, corresponding to the location relation on the floor map. SfM is performed on the video frames captured in each area. In this way, the system patrols and displays the positions of persons on the floor map, providing the user visualization of congestion in advance.

Fig. 4: An example of a floor map (Kansai University in japan)

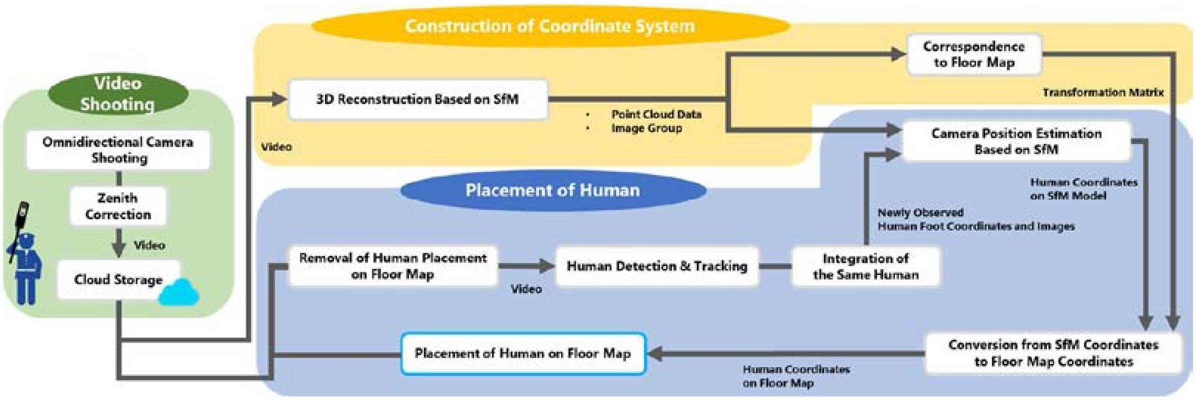

Fig. 5: Processing procedures by the proposed method

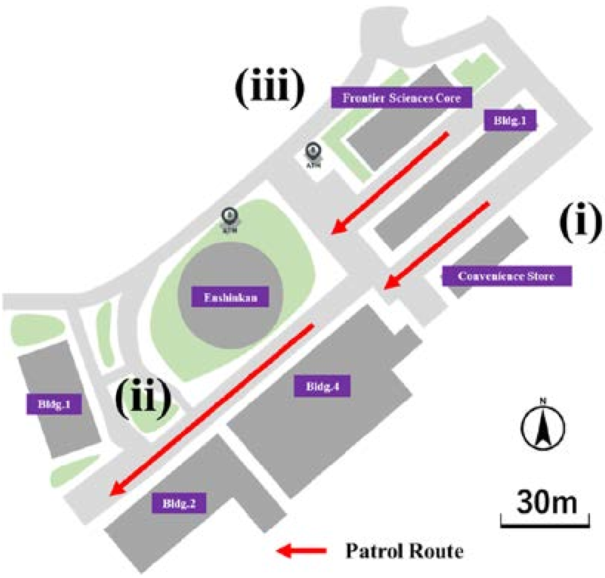

Fig. 6: Example patrol routes at the target site

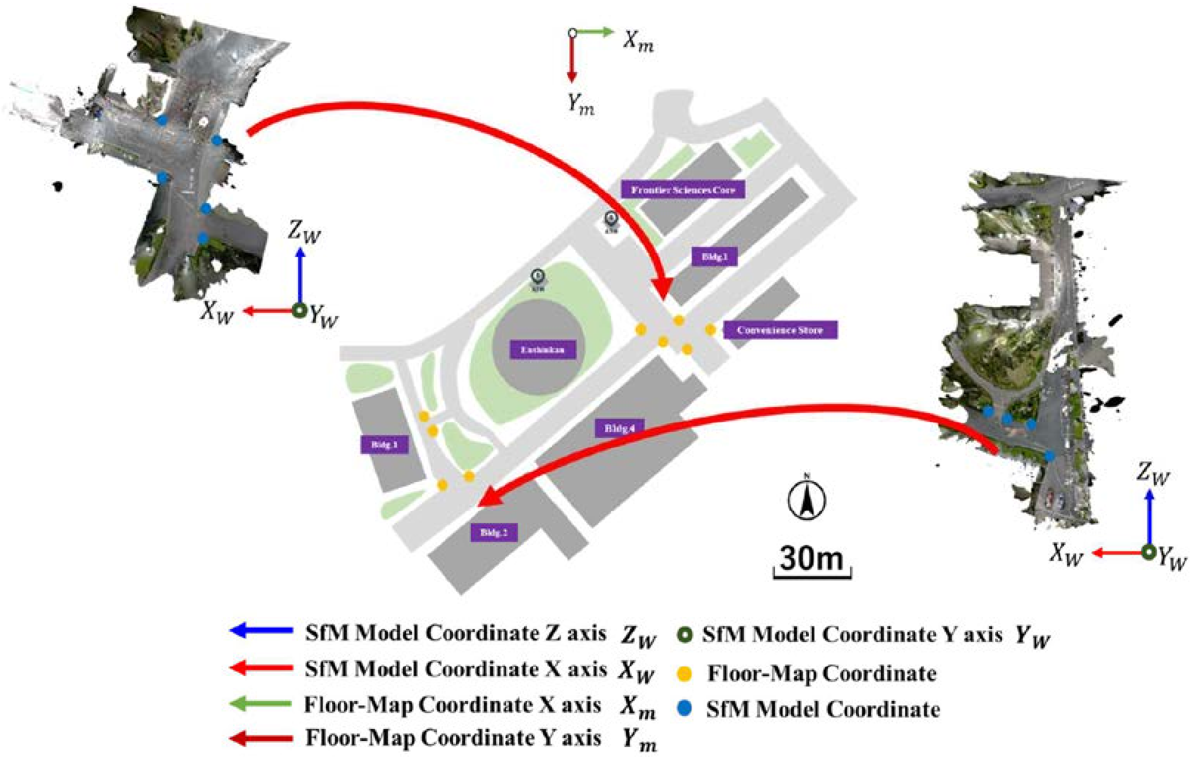

Fig. 7: Mapping examples of SfM model coordinates to the floor map coordinate

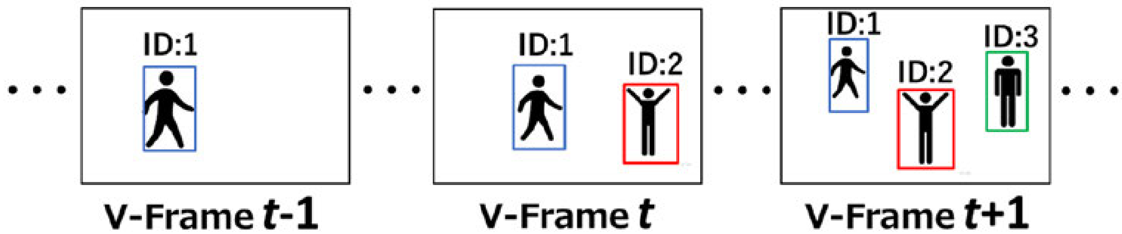

Fig. 8: Human detection and tracking through consecutive frames

2.2 Identification of the human's position

In identifying the standing position of a human on the floor map, the first step is to obtain the pixel positions (a, b) of the feet of the person in the omnidirectional image with width W px and height H px, as shown in Fig. 9. Since the height direction of the omnidirectional image corresponds to the Y_c axis of the camera coordinates through the zenith correction process, as shown in Fig. 10, let θ_1 be the angle between the vertically downward direction of the omnidirectional camera and the line-of-sight direction through the human's feet, and θ_2 be the azimuth angle of the person's feet based on the Z axis of the camera coordinates, $\theta_1 = \pi a/H$ and $\theta_2 = 2\pi b/W$ and The following is a calculation of the azimuth angle between the ground and the origin of the camera coordinates. Next, the height h from the ground to the origin of the camera coordinates is the difference between the Y_w coordinates of each camera and the Y_w coordinates of the point cloud of the ground detected by plane estimation using RANSAC (M. A. Fischler et al.,1981) on the point cloud data obtained by the 3D reconstruction process of the target site. In the X_c-Z_c plane of the camera coordinate system, if the distance from the origin to the person is d, the position of the human (X, Z) projected onto the X_c-Z_c plane is obtained by the following equation.

$$d = h \tan\theta_1 \qquad (1)$$

$$X = d \sin\theta_2 \qquad (2)$$

$$Z = d \cos\theta_2 \qquad (3)$$

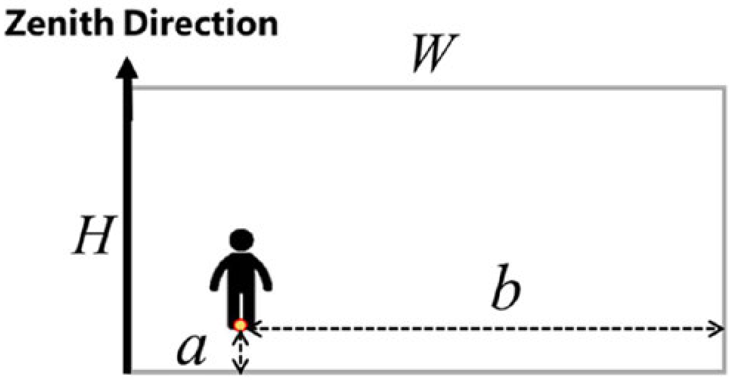

Fig. 9: Position of a person in an omnidirectional image

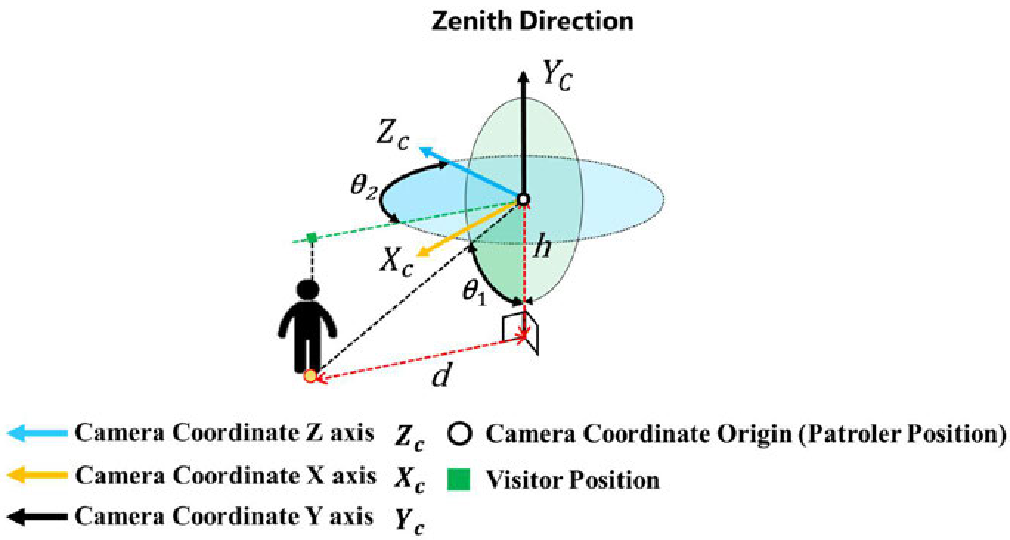

Fig. 10: Position of the camera and the person

Fig. 11 shows the relationship between the SfM model's coordinate system and each camera's coordinate system for each video record. The position of the camera coordinate system is the coordinate system calculated by SfM, which is also the position of the patrolman. Since the Y_c axis of the camera coordinate system and the Y_w axis of the SfM model correspond to the zenith direction, the positions of the persons detected at each shooting point can be integrated into the same coordinate system by rotation and translation on the X_w - Z_w plane. Let $R(\varphi)$ be the rotation and (t_x, t_z) be the camera position relative to the world coordinate; the position of a person (X_w , Z_w) in the 3D model can be calculated from the local camera coordinate (X ,Z) by equation (4).

$$\begin{bmatrix} X_w \\ Z_w \end{bmatrix} = R(\varphi) \begin{bmatrix} X \\ Z \end{bmatrix} + \begin{bmatrix} t_x \\ t_z \end{bmatrix} \qquad (4)$$

Next, the coordinate system X_m-Y_m plane of the floor map image of the facility and the X_W-Z_W plane of the SfM model coordinate system can be transformed into the position of the human on the SfM model by rotation φ_w around the Y axis in the SfM model coordinate system and translation shift, as before. Let S be a scaling matrix, R(φ_w) be a rotation matrix, and the origin coordinates (m_x, m_y) of the SfM model coordinate system in the X_m-Z_m plane and the human's position (X_m, Y_m) can be calculated as follows.

$$\begin{bmatrix} X_m \\ Y_m \end{bmatrix} = S \cdot R(\varphi_w) \begin{bmatrix} X_w \\ Z_{w'} \end{bmatrix} + \begin{bmatrix} m_x \\ m_y \end{bmatrix} \quad (5)$$

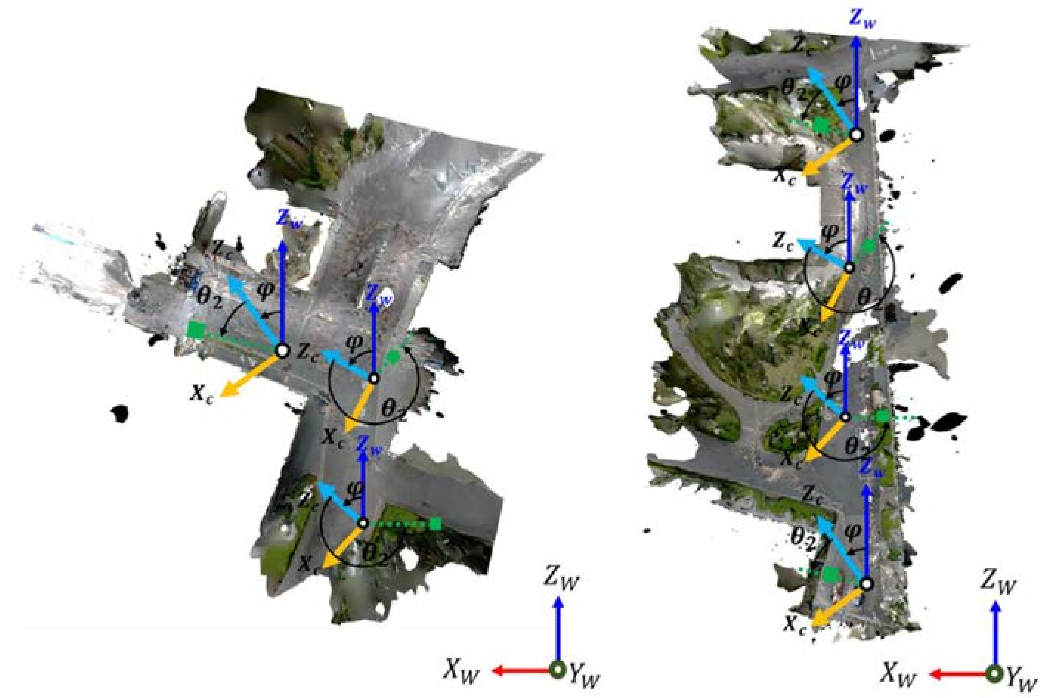

Fig. 11: Relationship between the SfM model coordinate X_w-Y_w-Z_w and the coordinates of the moving camera

3. EXPERIMENT

3.1 Equipment

For the experimental environment, we used a location in front of a convenience store on the Senri-yama campus of Kansai University (area (i) in Fig. 6), assuming a commercial facility crowded with many people. Theta X (RICHO) was used for the omnidirectional camera, with a video resolution of 5760 × 2880, Metashape Professional (Agisoft) for SfM, YOLO-X (Z. Ge et al.,2021) was used for the human detection model, and motpy (motpy - simple multi-object tracking library, 2022) was used for human tracking, as it is easy to combine various object detection models and OpenCV, an image processing library, was used to display the location of the person on the floor map of the target site.

3.2 Construction of coordinate system

As shown in Fig. 12, a 3D reconstruction based on SfM was performed using 91 images taken at the site, and a coordinate system was constructed. The average error was approximately 0.05 m. The number of tie points was approximately 4.7. The number of tie points was about 47,000, and the RMSE (root mean square error) of the re-projection of the feature points estimated from the image set onto the original image was about 3.0 pixels, indicating that the 3D shape is generally accurate. In the mapping between the coordinate system of the SfM model and that of the floor map, first, we visually picked up the corners of buildings and roads in each coordinate system to prepare five pairs of coordinates of (X_w, Z_w) and (X_m, Y_m). Next, the distance from the center of gravity of the five points to each of the five points in each coordinate was calculated, and the average value was calculated. There is a method to calculate the rotation matrix and translation vector in the point set matching problem by SVD (singular value decomposition) (K.S.Arum et al.,1987). In this study, $R(\varphi_w)$ and (m_x, m_y) are calculated by SVD. 5 points on the SfM model are transformed to positions on the floor map by equation (5). The results displayed on the floor map are shown in Fig. 13. The exchanged positions of the five points on the floor map generally corresponded to those of the five points on the SfM model.

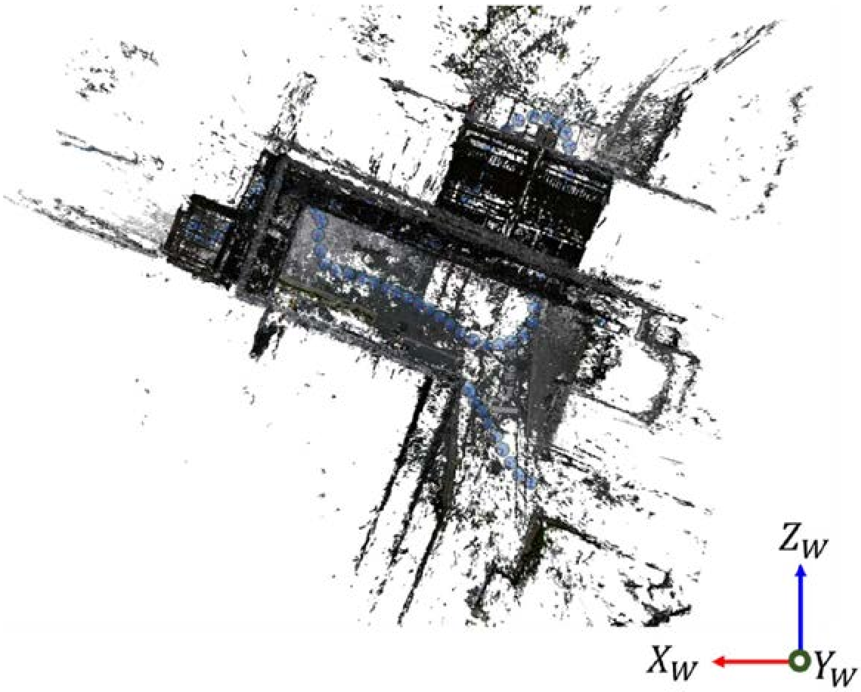

Fig. 12: 3D model and camera shooting position: The blue sphere indicates the shooting position.

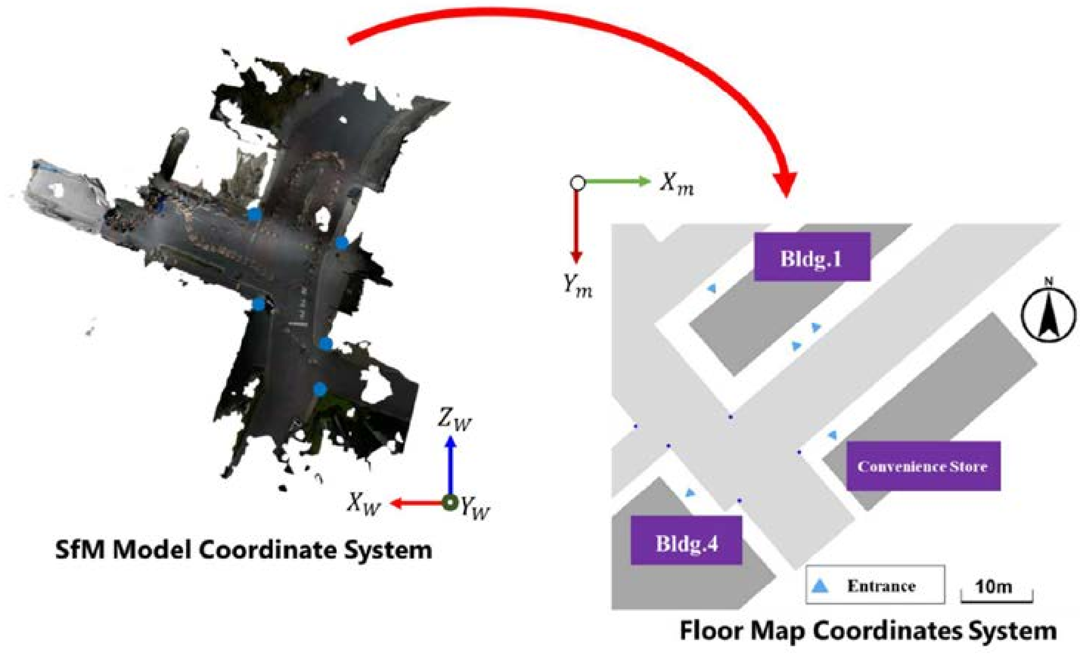

Fig. 13: Correspondence between SfM coordinate system and floor map coordinate system：
blue dots indicate 5 points in each coordinate system

3.3 Integration and display of person location information

YOLO-X was used for performing human detection for obtained image set from each section's video, as shown in Fig. 14. If the detected person has been tracked from a previous image frame by motpy using the video as input, the detected human is integrated into the existing person's information. If the human was not tracked and was newly observed, the observed image was used to estimate the camera position in the coordinate system of the SfM model, and the camera coordinates were calculated. The coordinates of the human's feet and the coordinates of the floor map were used to calculate the position coordinates of the human using Equations (1)-(5) and displayed on the floor map (Fig. 15, 16, and 17). The positions of the people mapped on the floor generally corresponded to the original images, and their positions about the buildings were also confirmed. However, because YOLO-X can detect people even in the case of body parts, and because the images are taken while moving, there are many cases where people in occlusion due to occlusion can be observed and mapped in other locations, making it possible to visualize the distribution of the people quantitatively. In addition, we were able to confirm changes in the degree of crowding at different times, such as around noon (Fig. 15), when the area is crowded at lunchtime, there is extreme crowding near the store entrance, many people move during class breaks (Fig. 16), and the area is empty during class (Figure17). Area (ii) in Fig. 5 was also patrolled around noon on the same day. The distribution of people observed was displayed on the floor map in the same manner as above (Fig. 18). As a result, it was possible to visualize the occurrence and resolution of queues and crowding of people near building entrances and the vicinity of stores, depending on the time of day. In a wide area, it was confirmed that information on the distribution of people could be updated for different areas in parallel by patrolling the area with several people. These functions are practical for visitors and others to know the trend of human distribution.

Fig. 14: Human detection using YOLOX for an omnidirectional image

4. CONCLUSION

In this study, we proposed a method for mapping and updating the distribution of people on a floor map in a fragmented manner, even over a wide area, simply by walking around the site and taking pictures with an omnidirectional camera and confirmed the method's effectiveness through experiments. The proposed method cannot perform synchronized observations because both the observer and the visitor are moving. However, it requires far fewer cameras and is equivalent to observing from many viewpoints because of the moving point observation. Therefore, parallel software processing of visitor observation and mapping will be highly cost-effective in terms of implementation and operation. Although the visitor mapping has time deviations depending on the location of the observation, visualization of the updated time together with the map will help understand the distribution of congestion. In future work, the authors plan to investigate a method of real-time mapping by online processing using the live streaming function of the camera and to construct a system that allows users to view maps showing the distribution of people on the Web.

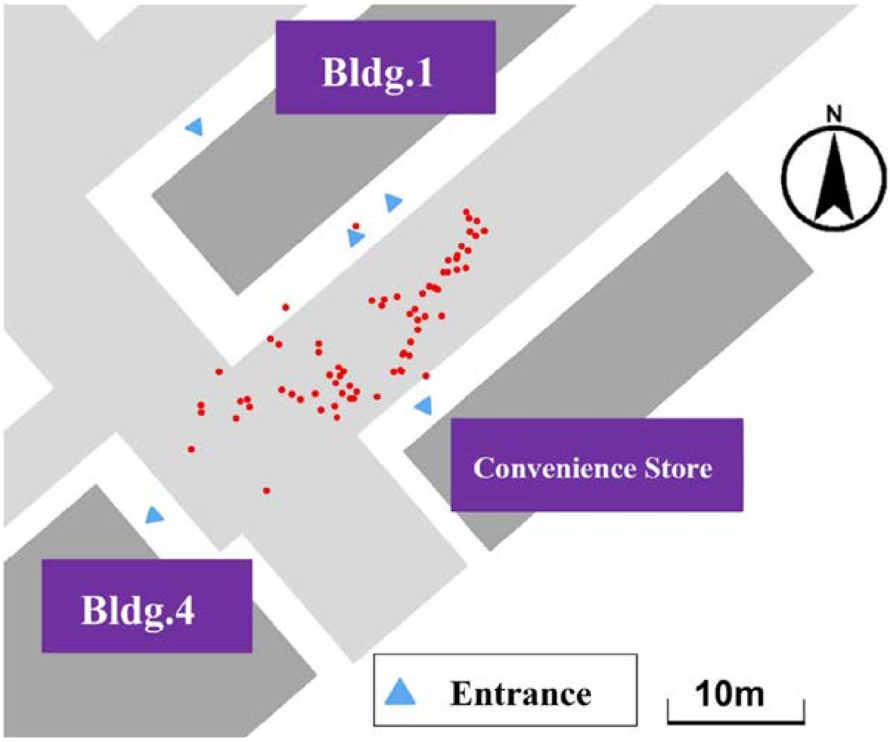

Fig. 15: Placement of people on the area (i) map: 12:00 PM:
Red dots indicate the visitor's location.

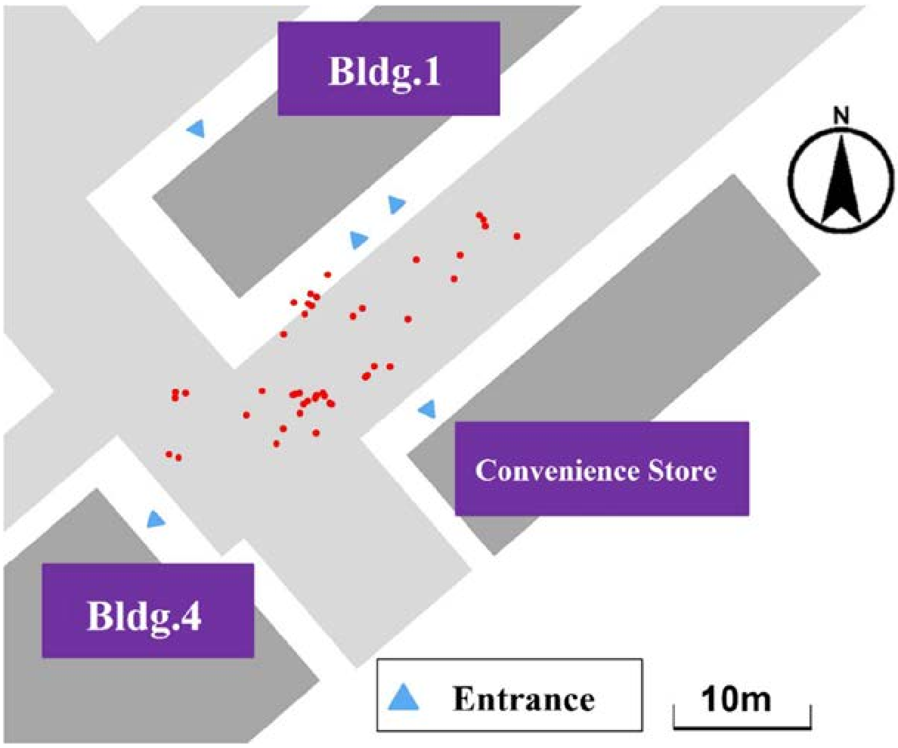

Fig. 16: Placement of people on the area (i) map: 2:30 PM:
Red dots indicate the visitor's location.

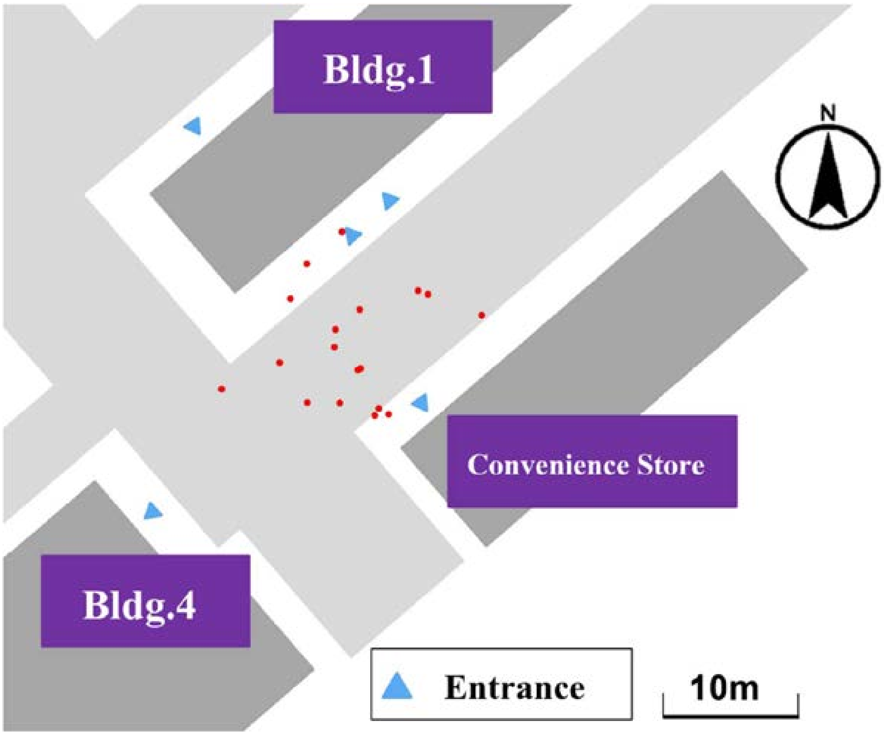

Fig. 17: Placement of people on the area (i) map: 4:00 PM:
Red dots indicate the visitor's location.

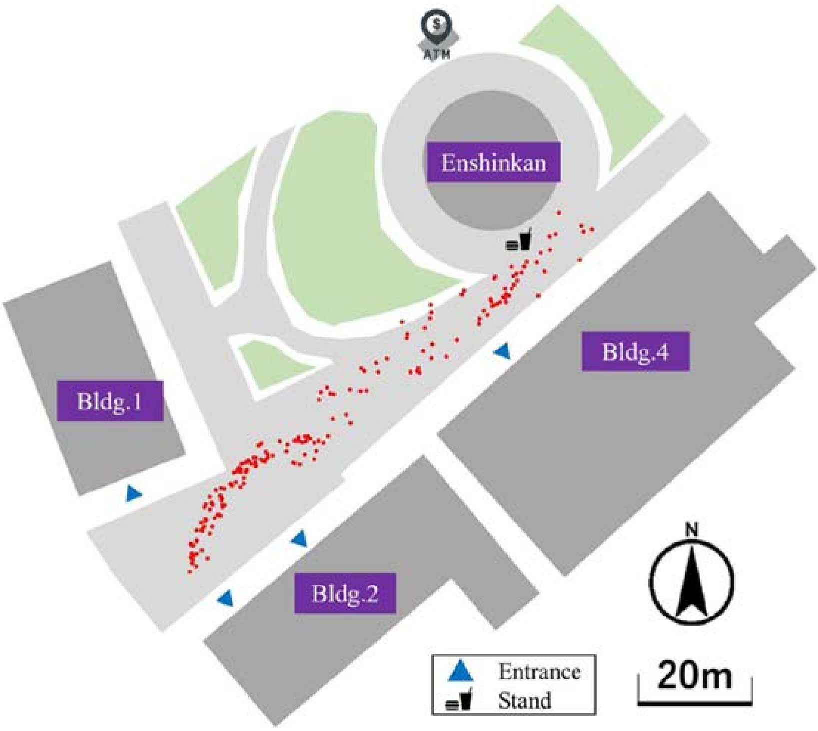

Fig. 18: Placement of people on the area (ii) map: 12:00 PM :
Red dots indicate the visitor's location.

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ISAFE WELDING SYSTEM: COMPUTER VISION-BASED MONITORING SYSTEM FOR SAFE WELDING WORK

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ABSTRACT: *The construction industry faces significant challenges, including a high prevalence of occupational incidents, often involving fires, explosions, and burn-related accidents due to worker non-compliance with safety protocols. Adherence to safety guidelines and proper utilization of safety equipment are critical to preventing such incidents and safeguarding workers in hazardous work environments. Consequently, a monitoring system tailored for construction safety during welding operations becomes imperative to mitigate the risk of fire accidents. This paper conducts a brief analysis of OSHA rules pertaining to welding work and introduces the iSafe Welding system, an advanced real-time safety monitoring and compliance enforcement solution designed specifically for construction site welding operations. Harnessing the real-time object detection algorithm YOLOv7 in conjunction with rule-based scene classification, the system excels in identifying potential safety violations. Rigorous evaluation, encompassing precision, recall, mean Average Precision (mAP), accuracy, and the F1-Score, sheds light on its strengths and areas for improvement. The system showcases robust performance in rule-based scene classification, achieving high accuracy, precision, and recall rates. Notably, the iSafe Welding system demonstrates a formidable potential for enhancing construction site safety and regulatory compliance. Ongoing enhancements, including dataset expansion and model refinement, underscore its commitment to real-world deployment and its strength in ensuring worker safety.*

KEYWORDS: *Safety monitoring, scene classification, welding work, fire prevention, construction safety, OSHA rules compliance*

1. INTRODUCTION

The construction industry exhibits a pronounced prevalence of both fatal and non-fatal occupational incidents on a global scale (Hussain et al., 2022; Khan et al., 2023). Among the significant contributors to these casualties and injuries are fires, explosions, and burn-related incidents, often stemming from workers' non-adherence to precautionary safety protocols during hot work. The primary causes of fires at construction sites encompass highly flammable substances, including foam insulation, gas cylinders, chemical storage facilities, and oil-based paints. The proximity of these materials to welding and cutting activities can serve as a precipitating factor for fires at construction sites (Xu et al., 2022). According to the Occupational Safety and Health Administration (OSHA) accident database, a total of 80 accidents occurred between July 2019 and July 2023 related to burning incidents at construction sites attributed to welding and cutting work. Among these recorded incidents, 22 were categorized as fatalities. These accidents occur when workers fail to utilize safety gear properly or neglect its use altogether, leading to exposure to various hazards such as chemical splashes, flying debris, intense light, harmful fumes, and more (Nill, 2019). For instance, during welding or cutting operations, the absence of proper eye protection can result in severe eye injuries, potentially leading to temporary or permanent vision loss. Additionally, if a worker does not take necessary precautions while performing welding or cutting tasks, and flammable materials or chemicals are stored nearby, there is a significant risk of explosions or fires at the workspace, posing serious harm to the worker. It is essential for workers to adhere to safety guidelines and utilize the appropriate safety equipment to prevent such incidents and safeguard their well-being in hazardous work environments.

Nowadays, computer vision (CV) techniques have found applications in monitoring construction sites across various construction scenarios (Jeong et al., 2017). However, with regard to welding processes, researchers have focused on areas such as identifying welding defects (Ramadan et al., 2023; Wu et al., 2023), welding bead detection (JOHN, 2023), detecting welding quality (Yang et al., 2018), and classifying welding types (S. Chen et al., 2023; H. Liu et al., 2023). Chen et al. proposed YOLOv5 based welding helmet use detection during the welding work (W. Chen et al., 2023). However, it is worth noting that there have been relatively limited efforts directed towards ensuring compliance with safety regulations or implementing monitoring mechanisms specifically during welding operations. Hence, the need for a comprehensive monitoring system in construction safety during welding operations is evident, primarily to mitigate the risk of fire accidents. To enhance safety at the construction site, this paper briefly analyzes OSHA rules related to welding work. Further, a computer vision-based monitoring system, "iSafe Welding System," is proposed to ensure compliance with safety protocols during

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Syed Farhan Alam Zaidi, Rahat Hussain, Muhammad Sibtain Abbas, Jaehun Yang, Doyeop Lee, Chansik Park, *iSafe Welding System: Computer Vision-Based Monitoring System for Safe Welding Work*, pp. 669-675, DOI 10.36253/979-12-215-0289-3.66

welding work. The Convolution Neural Network (CNN)-based You Only Look Once (YOLO) version 7 model is trained for the object detection module, and a rule-based algorithm is developed to assess safety rules compliance that classify the scene as “safe” or “unsafe”. Moreover, a new dataset is collected from construction jobsite, web image scrapping, and generated synthetic data from OpenAI’s DALL.E.2.

2. SAFETY RULE ANALYSIS

The OSHA rule 1910.252 pertains to hot work, encompassing welding, cutting, and brazing activities. This regulatory framework is forked into distinct sections: section (a) addresses fire prevention and protection, while section (b) is devoted to personnel protection, encompassing guidelines pertaining to personal protective equipment (PPE) usage and the safe positioning of welding cables and equipment. A careful examination of these regulations reveals that, during the execution of welding operations, workers are mandated to use welding-specific PPE. Furthermore, provisions necessitate the presence of a fire extinguisher in close proximity, the employment of fire prevention measures such as the utilization of fire prevention nets, a prohibition on the presence of insulation or foam in the safe area, and the maintenance of a safe distance from chemicals and gas cylinders during welding activities. For a comprehensive exposition of OSHA rule 1910.252 relevant to welding, along with an outlining of requisite detection objects, readers are directed to Table 1 for further interpretation.

Table 1. The details of OSHA rule 1910.252 related to welding and objects require for detection

Sr. No.	Rule Code	Description	Objects
	a) Fire prevention and protection		
1	(a)(1)(ii)	Use guards to confine heat, sparks, and slag	Fire prevention Net
2	(a)(2)(i)	Combustible Material - Prevent exposure to sparks through floor openings, cracks, walls, doorways, and windows	
3	(a)(2)(ii)	Fire Extinguishers - Maintain ready-to-use fire extinguishing equipment	Fire Extinguisher
4	(a)(2)(iii)(A)(1)	Combustible material in building construction or contents closer than 35 feet (10.7 m) to the point of operation.	Flammable Material
5	(a)(2)(iii)(A)(2)	Appreciable combustibles are more than 35 feet (10.7 m) away but are easily ignited by sparks.	
6	(a)(2)(iii)(A)(3)	Wall or floor openings within a 35-foot (10.7 m) radius expose combustible material in adjacent areas including concealed spaces.	
7	(a)(2)(iii)(A)(4)	Combustible materials are adjacent to the opposite side of metal partitions, walls, ceilings, or roofs and are likely to ignite.	
	b) Protection of personnel		
8	(b)(1)(ii)	Protection of Personnel - Clear placement of welding cable and equipment	Welding machine
9	(b)(2)(i)(A-D)	Eye Protection - Helmets or hand shields for arc welding and cutting	Worker and Helmet with eye shield (PPE)
10	(b)(2)(i)(B)	Eye Protection - Goggles or suitable eye protection for gas welding or oxygen cutting	
11	(b)(2)(i)(C)	Eye Protection - Transparent face shields or goggles for resistance welding or resistance brazing	
12	(b)(2)(i)(D)	Eye Protection - Suitable goggles as needed for brazing operations	

3. METHODOLOGY

This section describes the comprehensive methodology employed in the development and implementation of the “iSafe Welding system”, which comprises three main steps: dataset collection and preparation, training object detection model, and safety rules compliance. The details of these steps are as follows:

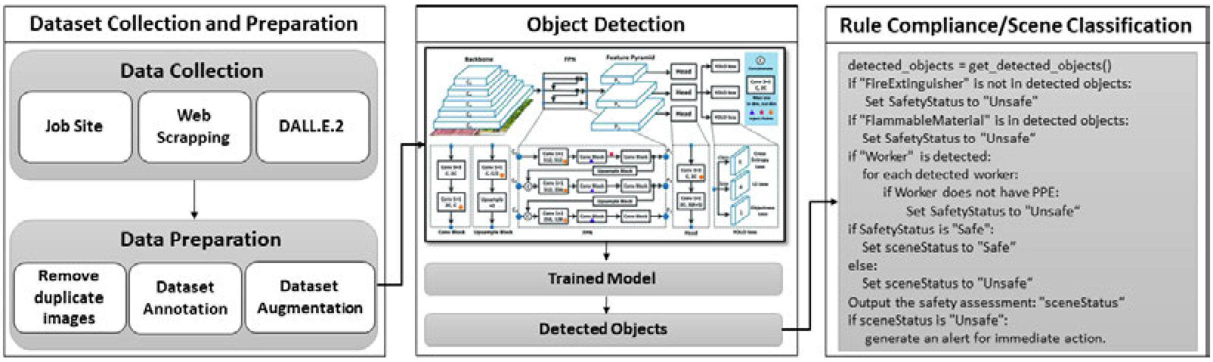

Fig. 1. Methodology for training iSafe Welding System

3.1 Dataset Collection and Preparation

The dataset employed in this research comprises 633 meticulously curated images collected from construction jobsite, web image scrapping, and generated synthetic data from OpenAI’s DALL.E.2. The dataset was divided into training (511), validation (61), and testing (61) sets for the iSafe Welding system. This dataset includes 1,935 annotated instances, categorized into five classes: “Welding Equipment” (621 instances), “Worker with PPE” (607 instances), “Welding Machine” (348 instances), “Fire Extinguisher” (197 instances), and “Flammable Material” (162 instances). These categories represent essential elements and scenarios within welding environments, emphasizing equipment, worker safety, welding machinery, fire prevention measures, and flammable material management. The roboflow platform is used for annotating dataset by drawing bounding boxes. For data augmentation, a series of transformative techniques are employed exclusively on the training dataset using roboflow. These augmentation methods included horizontal flip, shear, hue adjustment, brightness variation, exposure modification, cutout, and the mosaic technique. The training set was increased 3 times of original training set after augmentation.

3.2 Training Object Detection Model

In pursuit of real-time object detection capabilities, iSafe Welding has strategically adopted single-stage detection algorithms. These algorithms are renowned for their efficiency and speed, offering high frame-per-second (fps) rates for rapid and real-time object detection (Diwan et al., 2023). The decision to favor single-stage detectors over two-stage detectors aligns with the project's primary objective of ensuring swift and accurate detection of objects during welding operations within the construction industry. In the realm of real-time object detection algorithms, two prominent options, Single Shot Multibox Detector (SSD) (W. Liu et al., 2016) and the YOLO series detectors, were considered for this research work. After careful evaluation, the YOLO series detectors were selected as the preferred choice due to their notable strengths in achieving a commendable balance between accuracy, as measured by mean Average Precision (mAP), and fps rates. Specifically, YOLOv7 (Wang et al., 2023) was chosen as the model of preference for training, enhancing its capabilities to excel in the task of object detection, a critical component of the iSafe Welding system aimed at enhancing safety and compliance during welding operations in the construction industry.

YOLOv7 is a single-stage anchor-based object detector that uses a custom backbone network and a new head network. The basic YOLO model architecture (Long et al., 2020) is shown in the object detection module of Fig. 1. The backbone is a convolutional neural network (CNN) that extracts features from the input image. YOLOv7 uses a modified ELAN architecture for the backbone, which is more efficient and has better learning ability than the original ELAN architecture. The head is responsible for predicting bounding boxes and object classes. YOLOv7 uses a single-stage head, which means that it predicts bounding boxes and object classes directly from the features extracted by the backbone and neck. YOLOv7 uses a new anchor box selection algorithm that is more efficient and effective than the algorithm used in previous YOLO models. This helps to improve the accuracy of the model, especially for small objects. YOLOv7 has a reduced parameter count and computation compared to previous YOLO models. This makes it faster and more efficient to run on devices with limited resources (Wang et al., 2023).

The training process of the model was conducted using hardware resources consisting of an Intel Core i9-10900 CPU, operating at 2.80GHz, complemented by 32 GB of RAM, and further accelerated by the inclusion of an RTX 3090 graphics processing unit, boasting 24 GB of dedicated memory. The model was trained on 300 epochs, with a batch size parameter set to 16, and an input image size established at 640x640 pixels. In pursuit of model optimization, the YOLOv7 framework uses the default Stochastic Gradient Descent (SGD) optimizer, initialized with a learning rate of 0.01, culminating in a final learning rate of 0.1. Additional optimization parameters encompassed a weight decay factor of 0.0005 and a momentum coefficient of 0.9, collectively contributing to the refinement of the model's performance.

3.3 Safety Rules Compliance/Rule-based Scene Classification

After conducting an in-depth examination of the OSHA regulation regarding welding work, as detailed in Section 2, significant and crucial findings were obtained. It was determined that the presence of specific safety parameters significantly impacts the safety status of a welding scenario. Specifically, if a welding task is being executed and no fire extinguisher is positioned in proximity, or if flammable materials are detected in the surrounding area, the scene is deemed unsafe as per OSHA guidelines. Furthermore, any detection results indicating the absence of PPE on a worker subsequently flag the scene as unsafe. Upon completion of the object detection module, the results are seamlessly transitioned to the safety rules compliance module. Herein, a algorithm is developed to examine the adherence to safety rules, discerning whether the detected scenario should be categorized as safe or unsafe, effectively enhancing safety and compliance during welding operations within the construction industry. The algorithm is described in Algorithm 1.

Algorithm 1: Safety Rules Compliance Module

Input: Results from the object detection module, including detected objects and their attributes.

Output: Safety assessment for the detected welding scenario, categorized as "Safe" or "Unsafe."

```
1. Initialize a variable SafetyStatus to "Safe"
2. if "FireExtinguisher" is not in detected objects:      // Check for the presence of a fire extinguisher
       Set SafetyStatus to "Unsafe"
3. if "FlammableMaterial" is detected:                    // Check for the presence of flammable materials
       Set SafetyStatus to "Unsafe"
4. if "Worker" is detected:                               // Check for worker PPE
       for each detected worker:
           if Worker does not have PPE:
               Set SafetyStatus to "Unsafe"
5. if SafetyStatus is "Safe":                             // Perform a final safety assessment
       Set sceneStatus to "Safe"
   else:
       Set sceneStatus to "Unsafe"
6. Output the safety assessment: "Safety Assessment: sceneStatus"
7. if sceneStatus is "Unsafe":
       Log safety assessment results and generate an alert for immediate action.
```

4. EVALUATION AND DISCUSSION

The evaluation of the iSafe Welding system encompassed two key aspects: object detection performance and rule-based scene classification. These assessments aimed to validate the system's efficacy in real-time safety monitoring and compliance enforcement within construction site welding operations.

4.1 Object Detection Performance

In the context of object detection, essential metrics such as precision, recall, and mean Average Precision (mAP) were rigorously calculated to gauge the system's ability to accurately identify and localize objects of interest. Concurrently, accuracy and the F1-Score were employed for scene classification as "safe" or "unsafe." The results are presented in Fig. 2 and Table 2. A significant observation is the disparity in mAP scores between the validation and test sets. The validation set exhibited a notably higher mAP, suggesting a degree of overfitting to the training and validation datasets. This phenomenon highlights the need for model refinement to enhance generalization capabilities and ensure reliable performance in real-world scenarios. The class-specific analysis reveals that the "flammable materials" class achieved a perfect recall of 100%. This remarkable recall rate can be attributed to the dataset's inherent limitation, featuring only a single type of flammable material. Conversely, the "welding equipment" class exhibited a 67.4% mAP on the test set, primarily due to the small and slender nature of these objects, rendering them challenging to detect accurately.

Table 2. Result of object detection model on validation and testing set with confidence threshold 0.5

Dataset	**Precision %**	**Recall %**	**mAP@0.5 %**
Validation set	97.9	97.9	99.2
Test Set	80.5	92.6	88.5

Fig. 2. Object detection and scene classification results of iSafe Welding System

4.2 Rule-Based Scene Classification

The rule-based scene classification component of the iSafe Welding system demonstrated its effectiveness in categorizing scenes as "safe" or "unsafe." The testing dataset was thoughtfully divided into these two categories, yielding 14 images classified as "safe" and 47 as "unsafe." Applying Algorithm 1 to these scenes led to notable results. The achieved accuracy, precision, recall, and F1-score of 96.72%, 97.87%, 97.87%, and 97.8%, respectively, underscore the algorithm's proficiency in accurately classifying scenes based on safety criteria. These outcomes affirm the algorithm's potential to enhance safety compliance and enforcement in the context of welding operations.

4.3 Future Directions

To address the observed issue of overfitting and to further enhance the system's capabilities, future efforts will primarily focus on expanding the dataset. Additionally, while the dataset used in this study inherently ensures that all depicted workers are equipped with PPE, future dataset extensions will include instances of workers without PPE. Furthermore, this expansion will involve the inclusion of various flammable materials and augmenting the dataset with a more diverse set of welding scenarios set in varied environmental contexts. Such measures are anticipated to significantly enhance the model's generalization and real-world applicability. As the OSHA rules require proximity between welding equipment and flammable materials as shown in Section 2, the future work will utilize real-sense camera to find distance between objects to calculate safe distance. Further, the updated algorithm will classify scene as safe or unsafe based on the safe distance.

5. CONCLUSION

Computer vision techniques have emerged as valuable tools for enhancing safety and efficiency on construction sites. While previous research has concentrated on aspects such as defect identification, welding bead detection, quality assessment, and type classification, there has been a noticeable gap in addressing safety compliance during welding operations. This gap underscores the need for a comprehensive monitoring system to mitigate the risk of fire accidents and ensure compliance with safety regulations. This paper has provided a brief analysis of OSHA rules related to welding work and introduced the iSafe Welding System, a computer vision-based monitoring solution designed to uphold safety protocols during welding operations. The integration of the YOLOv7 model for object detection, along with a rule-based algorithm for safety rule assessment, represents a robust approach to classifying scenes as safe or unsafe. Furthermore, the creation of a new dataset, comprising data from construction job sites, web image scraping, and synthetic data generated using OpenAI's DALL.E.2, enhances the system's adaptability and accuracy. The evaluation results demonstrate the system's effectiveness in real-time safety monitoring and compliance enforcement within construction site welding operations, with high precision and recall rates. The iSafe Welding System offers the potential to significantly improve workplace safety in the construction industry. By addressing the critical need for safety monitoring during welding, this system contributes to a safer construction environment, reducing the potential for accidents and improving overall workplace safety. Its applications extend to various industries requiring safety compliance and object detection, making it a valuable asset for enhancing safety and efficiency in dynamic work environments.

ACKNOWLEDGEMENT

This research was conducted with the support of the "National R&D Project for Smart Construction Technology (No.23SMIP-A158708-04)" funded by the Korea Agency for Infrastructure Technology Advancement under the Ministry of Land, Infrastructure and Transport, and managed by the Korea Expressway Corporation.

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COMPUTER VISION-BASED MONITORING FRAMEWORK FOR FORKLIFT SAFETY AT CONSTRUCTION SITE

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ABSTRACT:

Efficient forklift operation is critical for construction site safety and project progress; yet, the construction industry deals with recurrent issues, including unauthorized forklift operation, operator drowsiness, visibility challenges, blind spots, and load placement errors. This paper introduces the "iSafe ForkLift," a comprehensive safety framework powered by computer vision, specifically designed to tackle these multifaceted safety challenges associated with forklift operations. The framework provides an array of integrated solutions, encompassing facial recognition for authorization, anomaly detection for behavior monitoring, stereo cameras for improved visibility, blind spot solutions, and load placement monitoring. Aligned with OSHA safety standards, it offers opportunities for enhanced forklift safety by addressing a broad spectrum of potential risks within a single, efficient framework. Systematically addressing multiple safety risks within this unified framework significantly elevates overall safety. Future studies should prioritize enhancing technology by merging computer vision with IoT to boost precision and safety, especially on challenging terrains, thereby elevating construction industry standards' reliability.

KEYWORDS: *Forklift operations, Computer vision, Safety framework, Operator drowsiness, Visibility challenges, OSHA standards, Regulatory compliance*

1. INTRODUCTION

The construction industry, characterized by its dynamic and complex nature, is a realm where innovation and risk coexist. Here, heavy earth-moving machines, including forklifts, are integral, performing tasks that are pivotal for project progression. Forklifts are indispensable tools in this regard, capable of swiftly transporting heavy loads to various locations within the site. However, the operation of such machinery is filled with risks. Accidents involving heavy earth-moving machines are not uncommon and have led to severe, sometimes fatal, consequences, underscoring the critical need for enhanced safety protocols. Approximately 75 to 100 workers lose their lives in forklift accidents annually, with an average of roughly 87 fatalities per year. This number has seen a nearly 30% increase over the past decade (Forklift Accident Statistics, n.d.). According to the OSHA database, 1117 accidents occurred just because of forklifts (OSHA, 2023a). Operating forklifts on construction sites poses various challenges and risks, from unauthorized personnel attempting to use them to blind spots and improper load placement. Notably, there has been a pressing need to propose a comprehensive solution for these challenges, yet no researcher has put forward an all-encompassing approach to address them concurrently.

iSafe ForkLift, a state-of-the-art monitoring framework powered by computer vision, is meticulously proposed to tackle the multifaceted safety challenges associated with forklift operations. The suggested framework provides a range of solutions: (1) Authorization through Face Recognition: Leveraging a camera installed within the forklift, the system ensures that only authorized personnel can operate the machinery. By utilizing advanced face recognition algorithms, it verifies the identity of the operator in real-time, preventing unauthorized access. (2). Anomaly Detection for Driver Behavior: Beyond just authorization, the system is equipped to monitor the behavior of the operator. Through anomaly detection algorithms, it can identify signs of Drowsiness. Detecting signs such as frequent yawning, heavy eyelids, or nodding off, which can be particularly dangerous when operating heavy machinery, Distraction or Physical Discomfort, or other abnormal behaviors, prompting immediate intervention. (3). Enhanced Visibility with Stereo Cameras: Addressing the perennial issue of sight blocks, stereo cameras are installed to provide drivers with a hidden view. This feature not only enhances visibility but also offers real-time data on the distance between the forklift tip and nearby objects, aiding in precise navigation. (4). Blind Spot Solutions: Blind spots, a significant hazard in forklift operations, are mitigated through strategically placed signalers or mirrors. Computer vision techniques continuously monitor these areas, ensuring that they remain clear and alerting the driver to potential obstructions. (5). Load Placement Monitoring: The proper placement of loads on the forklift's tipover is crucial for stability. Using cameras and computer vision techniques, the system assesses the positioning of loads, ensuring they are securely and correctly placed.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Muhammad Sibtain Abbas, Aqsa Sabir, Nasrullah Khan, Syed Farhan Alam Zaidi, Rahat Hussain, Jaehun Yang, Chansik Park, *Computer Vision-Based Monitoring Framework for Forklift Safety at Construction Site,* pp. 676-682, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.67

2. CURRENT MONITORING TECHNIQUES FOR SAFE FORK OPERATIONS

Forklifts encounter several safety challenges, particularly in dynamic construction environments where loading and unloading activities are prevalent. While forklifts find extensive utilization in construction, the risk of accidents in such contexts is significantly elevated compared to other operational settings. Presently, a range of monitoring techniques are employed to mitigate these safety concerns. While there isn't a specific study focused on checking the authorized forklift operators for driving, numerous authors have explored the issue of abnormal driver behavior. Much attention has been devoted to the development of methods for detecting anomalies in this context (Amin et al., 2023; Okan & Rigoll, n.d.). Blind spot problem has been addressed by different researcher, (Shete et al., 2021) The implementation of an ultrasonic sensor to detect nearby obstacles in a forklift is an effective safety measure. However, to address blind spots and obstacles approaching from corners, the integration of convex lenses at these specific locations becomes imperative. These convex lenses serve as additional visual aids, enhancing the forklift operator's field of vision and ensuring a more comprehensive obstacle detection system Moreover, established standards dictate that forklift operation is restricted solely to authorized personnel, representing a fundamental safety measure in this context. This paper investigates factors influencing forklift operator safety and efficiency, including energy usage, training, IoT integration, ergonomic considerations, and worker drowsiness (Mediavilla, 2023). Emphasizing the significance of the matter, previous research did not encompass critical aspects of forklift operations utilizing computer vision technology, such as driver authorization, detecting abnormal behavior, mitigating blind spots, and optimizing load placement. Nevertheless, OSHA has played a vital role in addressing these factors, recognizing that neglecting them can result in severe accidents. These considerations are pivotal in the context of safety rules analysis, a topic to be elaborated on in the following section.

3. SAFETY RULES ANALYSIS

OSHA has established several crucial safety standards for industrial truck operations to mitigate risks and ensure workplace safety (OSHA, 2023b). These standards include prohibiting unauthorized individuals from riding on industrial trucks (1910.178(m)(3) & 1910.178(l)(3)). This measure prevents potential accidents such as falls, entanglements, or collisions that could result from non-operators being on board. Additionally, operators are required to avoid driving industrial trucks toward individuals positioned in front of fixed objects (1910.178(m)(1)). This rule emphasizes the importance of operator awareness and vigilance to prevent collisions that could lead to severe injuries or fatalities. Operators are also expected to maintain a forward-facing orientation while operating industrial trucks (29 CFR 1910.178(n)(4) & 29 CFR 1910.178(n)(6)). This enhances visibility, reducing the risk of accidents, especially in areas with pedestrian traffic or confined spaces. Furthermore, proper load handling is emphasized through the standards that require loads to be secure and correctly positioned (29 CFR 1910.178(o)(1) & 29 CFR 1910.178(o)(2)). Ensuring load stability is vital in preventing accidents such as tip-overs, which can result in injuries, equipment damage, and hazardous material spills. Lastly, while not explicitly stated in the provided standards, it is crucial for drivers to remain attentive (Abnormal Behavior - General Rule). This means avoiding behaviors that could distract them or impair their ability to operate the vehicle safely, as such actions can lead to accidents and must be strictly prohibited. Table 1 outlines OSHA regulations, providing their associated particulars along with proposed solutions.

Table 1 Safety Rules for Forklift

Sr. No	OSHA Standards	Description	Case Scenario	Proposed Solutions
1	1910.178(m)(3) & 1910.178(l)(3)	No unauthorized operator riding on trucks	Unauthorized Person	Face Recognition
2	1910.178(m)(1)	Never drive trucks toward anyone in front of fixed objects	Struck by	Depth Estimation/Object Detection
3	29 CFR 1910.178(n)(4) 29 CFR 1910.178(n)(6)	The driver must face forward path	Blind Spot/Blocked Vision	Signaler/Barriers/Mirrors
4	29 CFR 1910.178(o)(1) 29 CFR 1910.178(o)(2)	Secure and properly positioned loads	Tip over	Measure distance of load placement on fork tip
5	General rule	Driver must be attentive	Abnormal Behavior	Anomaly Detection

4. PROPOSE FRAMEWORK

This paper introduces a safety-oriented computer vision framework comprising five distinct modules: Signaler Detection, Face Recognition, Anomaly Detection, Signaler Detection, Load Monitoring, and Visibility Enhancement. These modules are seamlessly integrated into a central server, responsible for processing and storing information in a database. Additionally, the system is designed to trigger alarms whenever an unsafe event is detected. The setup employs three cameras: Models 1 and 2 are affixed to internal cameras to monitor operators and identify abnormal behaviors, meanwhile Model 3 utilizes a depth camera mounted on the tip of a forklift to improve visibility and Models 4 and 5 are connected to the Signaler Detection and Load Placement Monitoring components, respectively as depicted in Figure 1.

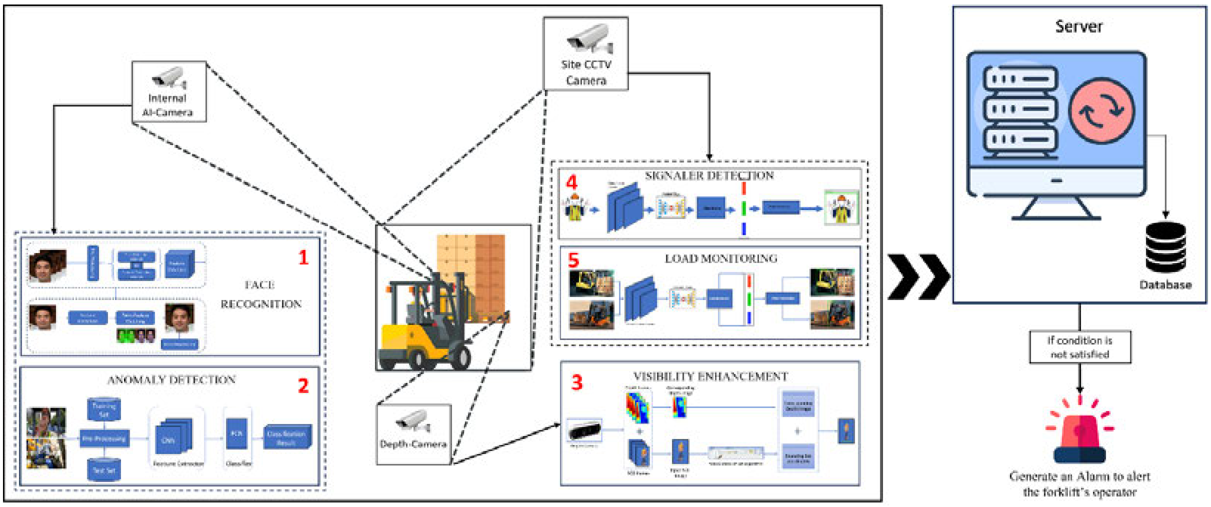

Figure 1: Forklift Operations Framework

4.1 Authorization through face recognition

The proposed framework for authorization employs an advanced facial recognition methodology for identity verification and access control, utilizing cutting-edge algorithms and computational methodologies to scrutinize facial features meticulously as shown in Figure . This comprehensive process initiates with capturing a facial image, subsequently contrasting the unique characteristics of this image against a meticulously curated database of stored facial templates. The seamless integration of state-of-the-art deep learning models, specifically Convolutional Neural Networks (CNNs) (Li et al., 2022), ensures the proficient extraction and meticulous analysis of detailed facial features, granting a high degree of accuracy and security in identity verification. This method emerges as crucial in numerous secure environments, providing swift and efficient determination of access eligibility predicated on the consequential recognition results. The scientific orchestration of our face recognition for authorization unifies the two stages first a facial feature database its elements are pre-processing (Bradski, 2000) to specify faces and feature extraction, attributing a unique ID to each face and storing these features for the second step. The second step involve inferencing for face detection for specific ID in a scenario its components are a deep learning-based feature extractor, a point based matching model (Lindenberger et al., 2023) and a detector for facial feature, while these are for detection part the post processing is crucial step which give authorization.

This amalgamation of techniques ensures the refinement of the recognition results. The subsequent post-processing step manages the comparison results, facilitating the final step of authorization, thereby enhancing the reliability and robustness of the system. In essence, our approach (Figure 2) in blending these advanced technologies and methodologies culminates in the development of a secure, reliable, and efficient system, pivotal in reinforcing security measures and averting unauthorized access. Through the utilization of precise feature comparison and advanced post-processing techniques, our objective is to offer a sophisticated solution that effectively addresses the diverse challenges associated with secure authorization.

4.2 Anomaly detection for driver behavior

In line with the objective of promoting safety and efficiency, the structured framework includes specialized anomaly detection algorithms. These algorithms are tailored to identify signs related to drowsiness, including driver fatigue, physical discomfort, and unusual behaviors requiring immediate attention. This is particularly crucial in scenarios involving heavy machinery operation within the construction industry, where such anomalies can escalate into significant safety risks and losses. The implemented algorithms meticulously observe and analyze various behavioral cues, such as the frequency of yawning, heavy eyelid drooping, moments of nodding off, or any behavior that deviates from the established norm. These cues indicate a potential decline in alertness or an increase in discomfort, both of which can adversely impact machinery operation. The proposed framework aims to identify drowsiness in forklift drivers by analyzing their facial expressions, as depicted in Figure . This system operates in real-time by collecting a dataset of images and labeling them for training purposes. The initial step involves enhancing the image quality and extracting relevant features through image pre-processing. For this purpose, a feature extractor based on the work of (Amir, Gandelsman et al., 2021) is employed. This feature extractor specializes in extracting detailed features from the facial images of drivers.

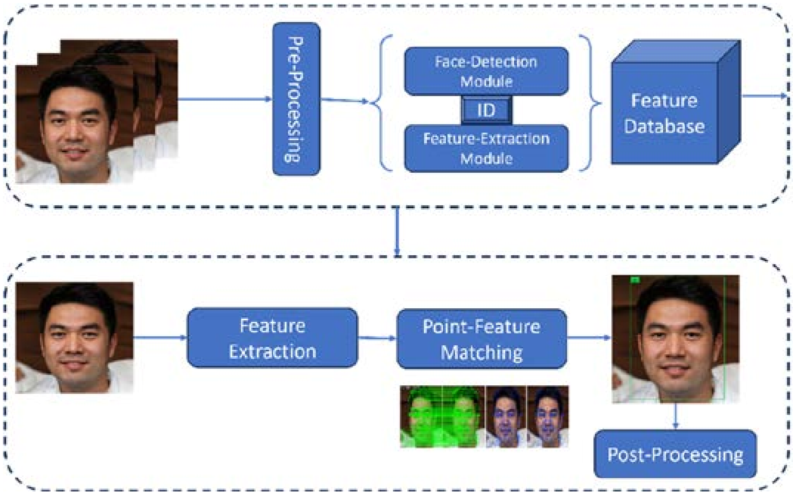

Figure 2: Face-Detection Framework for Authorization

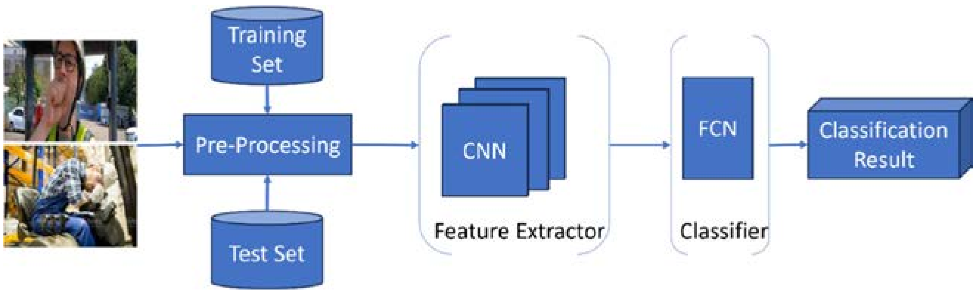

Figure 3: Framework for Forklift drowsiness detection

Once the features are extracted, a state-of-the-art deep learning model is utilized for classification. Specifically, a fully connected network, as described by (Schwing and Urtasun, 2015), is attached to the feature extractor. This network is trained to classify various images based on the driver's condition, distinguishing between normal and drowsy states. By utilizing deep learning, the system can learn intricate patterns and accurately categorize the driver's condition in real-time. After the classification step, a post-processing stage is implemented to activate an alert system based on the identified states. In practical terms, if the system detects drowsiness in the driver, it can promptly issue an alert or trigger a warning mechanism. This rapid response is crucial for preventing potential safety hazards, as it enables corrective actions or interventions to be initiated before accidents or injuries occur.

The application of advanced computational techniques and deep learning models enables the system to achieve a high level of precision in detecting driver states. It can effectively differentiate between normal and unusual behaviors, thereby ensuring the safety and well-being of individuals involved in forklift operations within construction sites. By promptly recognizing and addressing drowsiness, the system contributes to maintaining an overall safe working environment in construction settings.

4.3 Enhanced visibility with stereo cameras

In the scenario depicted in Figure , a challenge arises when the forklift is loaded, blocking the operator's direct line of sight to the area directly in front of the forklift. To tackle this issue, a stereo camera system will be installed at the front of the forklift's fork tip. This setup not only offers an unobstructed view of the concealed area but also employs computer vision-based object detection algorithms, such as yolov8 (ultralytistic, n.d.), to identify objects and determine their distance from the forklift. This comprehensive approach enhances safety by addressing vision obstruction concerns when the forklift is carrying a load.

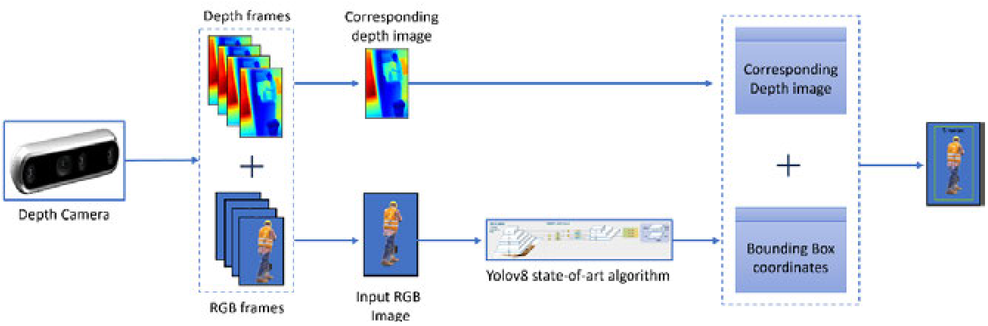

Figure 4: Visibility Framework with stereo camera

4.4 Blind spot solutions

Blind spots that arise when objects approach a forklift from a corner, as illustrated in Figure necessitate specific safety measures. In compliance with [29 CFR 1910.178(n)(4)] and [29 CFR 1910.178(n)(6)] mentioned in (OSHA, 2023b), it is essential to install signalers and convex lens mirrors at every corner within the work area where forklift operations take place. These signalers can be monitored through object detection technology. If a signaler is absent or not in its designated location, an alert message is generated, indicating unsafe conditions.

To ensure comprehensive coverage of the construction site where forklifts operate, multiple cameras need to be strategically installed. These cameras are connected to a server via RTPS (Real-Time Publish-Subscribe) protocol, and an object detection model is deployed on the server to enhance safety and monitor blind spots effectively.

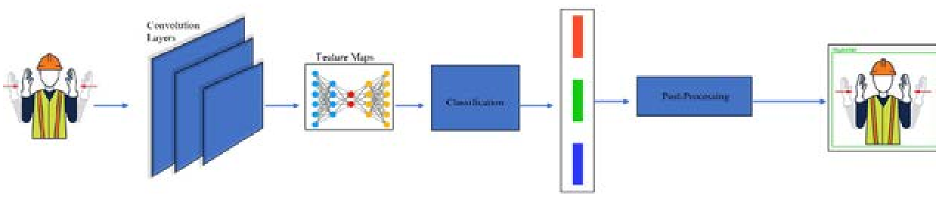

Figure 5: Signaler Detection

4.5 Load placement monitoring

Properly centering the load on a forklift is essential for safety, as highlighted in OSHA's 29 CFR 1910.178(o)(1) and 1910.178(o)(2) regulations. Incorrect load positioning increases the risk of tipping over, potentially causing operator injuries, equipment damage, and harm to nearby structures. Maintaining load stability and preventing tip-over accidents are critical.

Extensive research on forklift safety underscores the significance of load centering. Misalignment of loads elevates the risk of tip-overs, diminishes stability and maneuverability, and can lead to structural damage and injuries.

Adhering to OSHA regulations is imperative. Gavanski's 2022 study identifies safety concerns with forklifts, serving as a valuable reference for safety enhancements (Gavanski, 2022). Furthermore, Xia et al. (2023) introduced a center of gravity estimation algorithm for counterbalanced forklifts, achieving precise position control (Xia et al., 2023).

In this study, we introduce a computer vision-based framework (Figure 6) to oversee forklift operations during material loading and unloading. Utilizing advanced computational techniques and deep learning models, this system accurately identifies objects and reliably estimates the distance between the load's central point and the forklift's front wheel. The proposed framework plays a crucial role in enhancing safety at construction sites, benefiting both forklift operators and the machinery itself. Its primary function is to promptly detect and correct any load positioning issues relative to the forklift's mast, contributing significantly to a safe construction site environment.

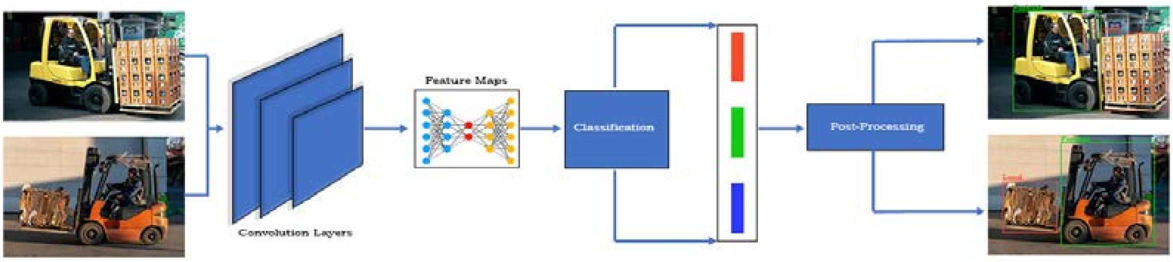

Figure 6: Forklift and Load Detection

5. DISCUSSION & CONCLUSION

The "iSafe ForkLift" framework represents a comprehensive solution aimed at enhancing safety in construction site forklift operations through the integration of advanced computer vision technology. This integrated system encompasses sophisticated features such as facial recognition for driver authentication, anomaly detection to mitigate operator drowsiness, stereo cameras to augment visibility, blind spot solutions, and load placement monitoring to preempt tip-over incidents. This framework stands out due to its holistic approach, a departure from conventional solutions that primarily address safety concerns individually. By systematically addressing multiple safety risks within a singular, efficient framework, it significantly enhances overall safety. However, there are certain limitations that necessitate careful consideration and foster discussions on technology, costs, safety, and compliance, with iSafe ForkLift improving forklift operations and worker well-being. The effectiveness of the framework is contingent upon the dependability of its technology, which may be vulnerable to adverse environmental conditions. Challenges may arise in accurately distinguishing between workers and signalers through computer vision. Acceptance among operators, coupled with concerns regarding data security and privacy management. Pertinent factors such as initial investment costs, ongoing maintenance, and operator training may pose challenges. Furthermore, the framework beckons opportunities for refinement, particularly concerning the reduction of false positives in anomaly detection and scalability. Following OSHA's safety protocols significantly boosts workplace safety. The integration of computer vision and IoT technologies enhances operational precision, while vigilance on uneven or challenging surfaces ensures stability and safety, thereby augmenting overall safety in the dynamic construction industry. In future work, we will delve deeper into these regulations by introducing dedicated computer vision solutions to enhance forklift safety across various industries.

ACKNOWLEDGEMENT

This research was conducted with the support of the "National R&D Project for Smart Construction Technology (No.23SMIP-A158708-04)" funded by the Korea Agency for Infrastructure Technology Advancement under the Ministry of Land, Infrastructure and Transport, and managed by the Korea Expressway Corporation.

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AUTOMATED EXTRACTION OF BRIDGE GRADIENT FROM DRAWINGS USING DEEP LEARNING

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ABSTRACT: *Digital methods such as Building Information Modeling (BIM) can be leveraged, to improve the efficiency of maintenance planning of bridges. However, this requires digital building models, which are rarely available. Consequently, these models must be created retrospectively, which is time-consuming when done manually. Naturally, there is a great interest in the industry to automate the process of retro-digitization. This paper contributes to these efforts by proposing a multistage pipeline to automatically extract the gradient of a bridge from pixel-based construction drawings using deep learning. The bridge gradient, a key element of the structure's axis, is critical for describing the elevation profile and axis slope. This information is implicitly contained in the longitudinal view of bridge drawings as gradient symbols. To extract this information, the well-established object detection model YOLOv5 is employed to locate the gradient symbols inside the drawings. Subsequently, EasyOCR and heuristic rules are applied to extract the relevant gradient parameters associated with each detected symbol. The extracted parameters are then exported in a machine-interpretable format to facilitate seamless integration into other applications. The results show a promising 98% accuracy in symbol detection and an overall accuracy of 70%. Consequently, the pipeline represents a significant advance in automating the retro-digitization process for existing bridges by reducing the time and effort required.*

KEYWORDS: *Building Information Modeling, Computer Vision, Deep Learning, Symbol Detection, Optical Character Recognition, Construction Drawings*

1. INTRODUCTION

Bridges play a central role in the transport network, as they are an essential element that creates connections and thus enables the transport of people and goods. To ensure their functionality and safe operation, regular inspections and effective maintenance management are of utmost importance. To support efficient maintenance planning, digital methods such as Building Information Modeling (BIM) can be employed. BIM refers to a digital collaboration method based on the creation and interdisciplinary exchange of digital building models (Borrmann et al., 2018). These models combine semantic information with geometric representations, acting as a single and central source of continuously enriching project information. Informed decisions can thus be made based on accurate and current data. Despite the potential BIM offers for all lifecycle phases, especially for the operation and maintenance (O&M) phase, it is most commonly used in the design phase of a construction project (Durdyev et al., 2022).

The limited utilization of BIM in the O&M phase arises from the requirement for digital as-built models of the structure, which are often not available. In many cases, this is due to the fact that the buildings were designed and constructed without the implementation of BIM. Therefore, these models have to be created retrospectively. Since this is a time-consuming manual task, there is a major research effort to assist or automate the process through the use of artificial intelligence (Schönfelder et al., 2023).

While many different sources of information can be used to create a digital building model of an existing structure, construction drawings are the most accessible. They not only contain geometric and semantic information about the building but also describe the internal structure of the components or building elements that are obstructed, e.g., buried underground. Therefore, drawings are an important source of information. This research contributes to the automatic creation of digital models from construction drawings by proposing a multi-stage pipeline for the automatic extraction of bridge gradient information from pixel-based construction drawings.

The bridge gradient illustrates the elevation profile of the bridge's axis and is, therefore, an essential information for a precise reconstruction of the superstructure's geometry. The course of the gradient is contained in the longitudinal view. It is implicitly described through gradient symbols that hold important details about elevation and slope at specific points along the bridge axis. Therefore, the pipeline encompasses several stages to automatically extract the gradient information from multiple locations and link the information. First, the pipeline utilizes state-of-the-art deep learning-based methods to detect the gradient symbols within the drawings. Subsequently, the text information associated with each symbol is extracted using optical character recognition

Referee List (DOI: 10.36253/fup_referee_list)
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Hakan Bayer, Benedikt Faltin, Markus König, *Automated Extraction of Bridge Gradient from Drawings Using Deep Learning,* pp. 683-690, DOI 10.36253/979-12-215-0289-3.68

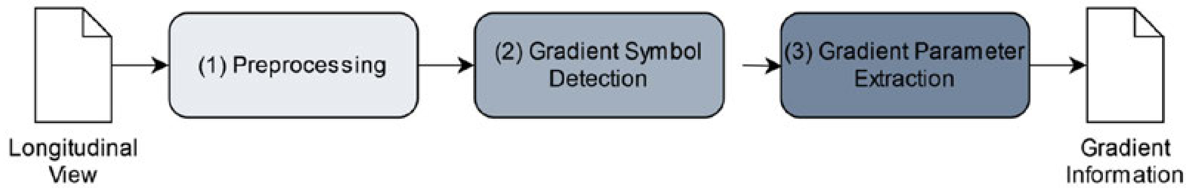

Fig. 1: Workflow diagram of the multi-stage pipeline for extracting the gradient of the bridge axis.

(OCR). Finally, the information is consolidated and harmonized into a structured data schema. The paper gives insight into the individual process steps and evaluates the performance of the proposed pipeline on a set of real-world bridge drawings.

The remaining sections of the paper are organized as follows: Section 2 reviews recent research publications on automatic reconstruction of digital models from drawings. The implemented pipeline is described in Section 3, with a detailed explanation of each step. Section 4 shows the results obtained when applying the proposed pipeline to real drawings. Finally, Section 5 discusses the results and limitations of this study and outlines a perspective for further research.

2. RELATED WORK

So far, little research has been published on digitizing technical drawings (Moreno-Garcia et al., 2019). Only a few of these publications deal with the (semi-)automatic analysis of drawings for infrastructures. Poku-Agyemang & Reiterer (2023) proposes a semi-automated process that utilizes the Douglas-Peucker algorithm to detect the corner points of illustrated components. These points are then used to reconstruct the component exterior edges, ultimately creating the bridge's geometry. A different semi-automatic framework is proposed by Akanbi & Zhang (2022). The proposed process involves converting the drawings into a vector-based data format, aligning the contained views, and finally using the extracted information to reconstruct the bridge's geometry. The reconstructed digital model is exported in the IFC (Industry Foundation Classes) data format. An approach based on deep learning methods is introduced by Mafipour et a. (2023). The authors present a pipeline employing YOLOv5 and CRAFT to automatically detect the individual components and texts in the drawings. The detected objects are then clustered based on their labels, as each component may appear in different views of the structure. These views are provided to an expert who uses this information to create the bridge based on a predefined parametric model manually. In contrast, Faltin et al. (2023) proposes a different approach for linking the views in construction drawings. The authors utilize FasterRCNN for detecting section symbols that illustrate the interconnections between views. Each detected symbol is uniquely identified through the section reference, allowing it to be mapped to the corresponding view using OCR on the view title. The interconnections are established across all views contained in a drawing set for a specific structure.

Overall, a larger number of publications exist on the reconstruction of high-rise building models from drawings. Wei et al. (2022) proposes a pipeline for detecting and reconstructing walls from floor plans. Firstly, the drawing is divided into patches, and the ResNet model is employed to identify patches containing walls. The walls are then detected in the positive patches using YOLOv3. All detections are merged to enable the utilization of Dynamo to create the digital model. Similarly, Zhao et al. (2020) uses the YOLO object detector to locate structural elements in the column structure and generate framework plan images. In a subsequent study, Zhao et al. (2021) continues the research by incorporating the superior Faster R-CNN model and introducing the creation of an IFC file from the extracted information. Kim et al. (2021) propose an approach for the detection of rooms, walls, and openings in floor plan images. The authors use a conditional generative adversarial network to create a heat map of the intersections and perform a style transfer to the floor plan image. Using the heat map of the connection points, the walls and openings are vectorized, which provides important information for recreating the building geometry.

However, to the best of the author's knowledge, no publication has been made that addressed the extraction of the bridge gradient from pixel-based drawings. This research aims to close the identified gap.

3. METHODOLOGY

A detailed explanation of the implemented methods is provided in the following section. Fig. 1 presents an overview of the proposed process. The input for the pipeline is a pixel-based longitudinal view of the bridge, as it contains the required gradient information. In this paper, it is assumed that the view has already been extracted from the complete drawing set, which the engineer can do manually in advance. The pipeline first preprocesses (1) the view by dividing it into smaller patches to enable the symbol detection. The gradient symbols (2) are detected within these patches, and for each symbol, the associated gradient parameters (3) are extracted. Finally, the information is exported in a structured format to facilitate its utilization within BIM modeling software.

3.1 Dataset Creation and Annotation

To detect the gradient symbol in the drawings, the state-of-the-art object recognition network YOLOv5 (Jocher et al., 2022) is employed. Training the network requires a dataset of bridge construction drawings manually annotated with the gradient symbol. However, since the gradient symbol only occurs in small numbers in a longitudinal view, this results in a limited number of training data points. This is insufficient to receive a well-trained model. Therefore, the training data is synthetically generated, using a copy-and-paste strategy following Faltin et al. (2023). The real annotated data is only used to test the network.

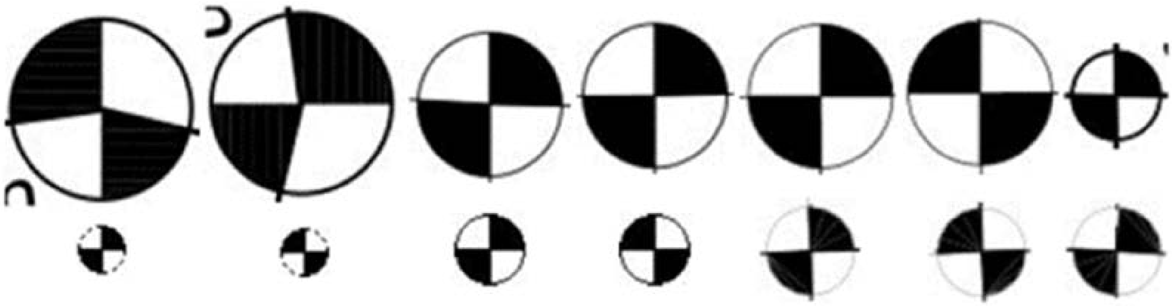

Fig. 2: Variation in created gradient symbols, sizes ranging from 85x85 to 20x20 pixels.

For the synthetic data, a template set of 14 unique gradient symbols is created and employed in the process (cf. Figure 2). These symbols vary in size from 85x85 to 20x20 pixels, shape, and texture, providing increased diversity in order to improve the models' ability to generalize.

The gradient symbol is chosen from the available template set and is randomly inserted into the background images. These background images are randomly cropped from bridge construction drawings which do not contain the gradient symbol and consist of various segments of construction drawings with different pixel sizes. To ensure compatibility with the YOLOv5 model, the background images are uniformly cropped to a standardized size of 640 x 640 pixels. This process is repeated multiple times to generate different combinations enhancing the diversity of the synthetic dataset. Fig. 3 presents some exemplary results of the method.

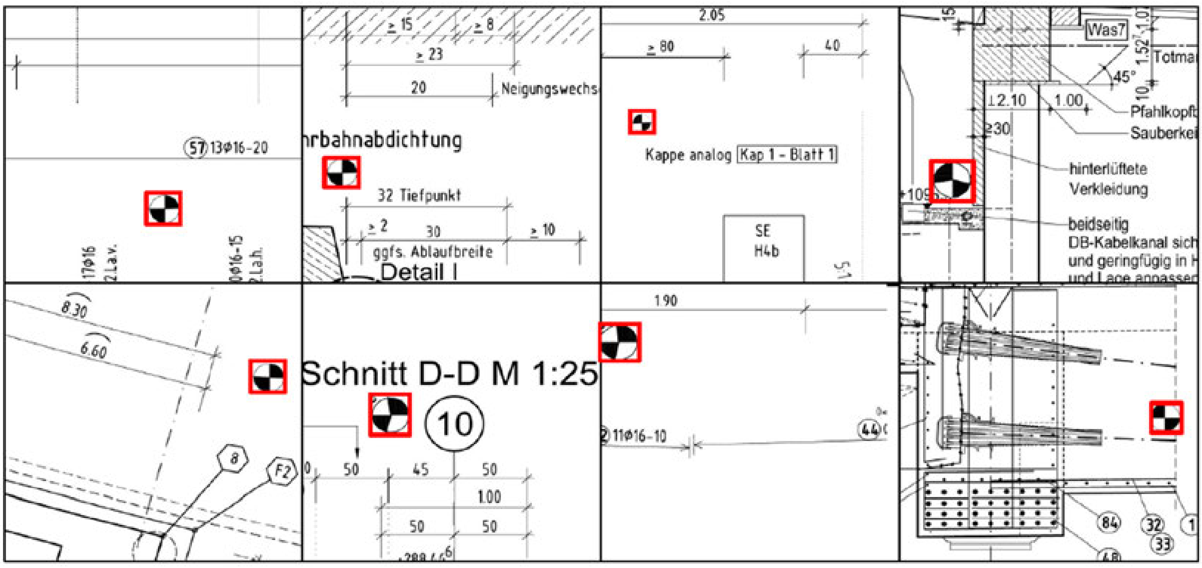

Fig. 3: Exemplary training images with a side length of 640 by 640 pixels synthetically generated using the proposed copy-paste method.

In total a number of 980 training images and 280 validation images are generated, resulting in the dataset named *Symbols*. Additionally, 62 real different images extracted from real bridge drawings are used for testing. According to Jocher et al. (2022) adding up to 10% of empty background images to the training and validation dataset enhances the object detection performance. Hence, 128 images are added to the training data, while 32 images are added to the validation data. This dataset is called *Symbols+BG*. Table 1 provides an overview of the final datasets.

Table 1: Overview of the generated data sets. Synthetic images are only used for training and validation.

	Content	No. of synth. training images	No. of synth. validation images	No. of real testing images
Symbols	Symbols only	980	280	62
Symbols+BG	Symbols and empty background	1108	312	62

3.2 Preprocessing and Gradient Symbol Detection

In order for the YOLOv5 model to handle the large image sizes of the input longitudinal views, a sliding window approach is employed. As shown in Fig. 4, as a first step a 640 by 640 pixel sized window is shifted across the image in increments of 330 pixels, ultimately covering the entire image. This step ensures that the gradient symbol is displayed in its entirety in at least one window, improving the detection performance. The trained YOLOv5 detector individually processes the windows, and the detected symbol is recorded. In cases where a symbol is detected in multiple overlapping windows, non-maximum suppression is employed to mitigate the possibility of double detections. For the final detections, rectangular regions are cropped from the original input image, extending 330 pixels in each direction (see Fig. 4), which is found to be sufficient. These cropped regions are further processed in the gradient parameter extraction, as explained in the following section.

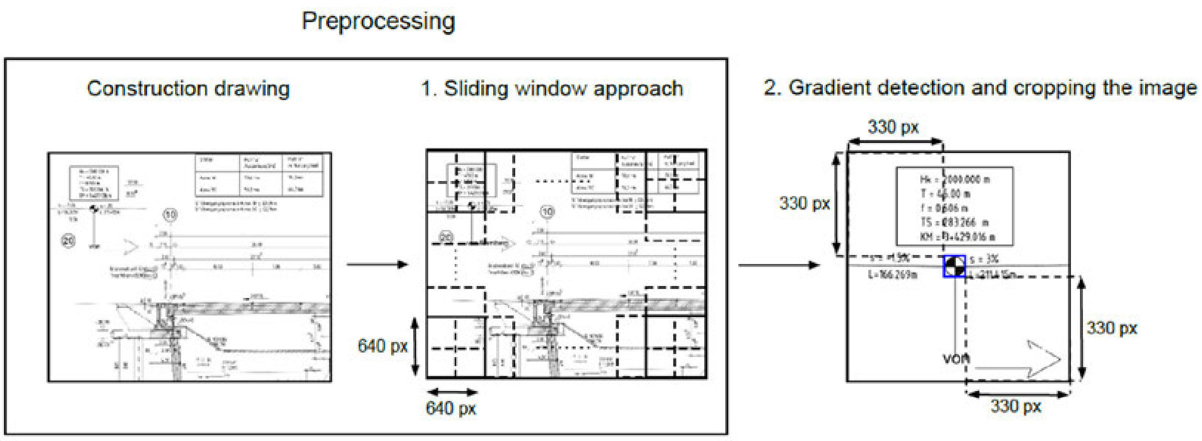

Fig. 4: Preprocessing of the construction drawing and detecting the gradient within the cropped area.

3.3 Gradient Parameter Extraction

After detecting the gradient symbols, the associated gradient parameters are extracted. To reliably recognize the parameters, the EasyOCR[1] text recognition model is used. EasyOCR combines the CRAFT (Baek et al. 2019) network and the text recognition network CRNN (Shi et al. 2018), since it is specifically designed for OCR. Therefore, EasyOCR provides robust capabilities for recognizing and extracting text from images. EasyOCR is employed in each region, as provided by the results from section 3.2. Within these regions, the text may appear rotated, reducing the EasyOCR model's recognition accuracy. To address this issue, the OCR engine is employed on the original region and a 90-degree rotated version. In addition, various image pre-processing techniques, e.g., adjustments to brightness and contrast, are applied to further improve the text recognition results.

An additional challenge is that not all text in the regions is relevant for the gradient reconstruction. Therefore, to ensure that only the relevant text is detected for further analysis, filtering, and string-matching techniques are implemented.

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[1] EasyOCR: https://github.com/JaidedAI/EasyOCR (Accessed 1 August 2023).

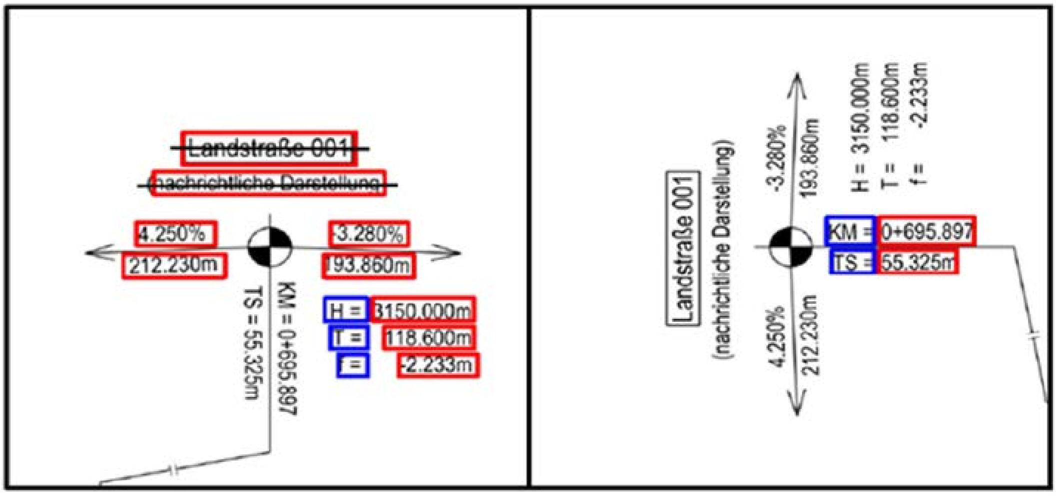

Fig. 5: Exemplary representation of the recognized texts in the original (left) and 90° rotated (right) patches. The recognized texts are marked in red, and the parameters are marked in blue. The crossed-out text passages cannot be assigned to any parameter and are, therefore, ignored.

In Fig. 5, the process of rotation, filtering, and string-matching is demonstrated. For instance, the text 'Landstraße 001' is irrelevant for the gradient detection and thus discarded. This filtering process is accomplished by identifying specific characters, such as *KM, TS,* or *T*, as depicted by blue in Fig. 5. Subsequently, the values that appear in the same horizontal line (cf. Fig. 5 marked with red rectangles) are matched with the identifying specific characters. In contrast, values located far away from the clusters are discarded. This process filters out unwanted text so that only relevant information is used in further analysis.

4. TRAINING & RESULTS

4.1 Training Process

Three different model sizes of YOLOv5 are trained and their performance is compared: YOLOv5m, YOLOv5l, and YOLOv5x. Each model trains on both the *Symbols* and *Symbols+BG* dataset using a NVIDIA A100 SXM4 40 GB graphics card. The models trained on Symbols are referred to as YOLOv5m, YOLOv5l, and YOLOv5x, while the ones trained on Symbols+BG are denoted as YOLOv5m_b, YOLOv5l_b, and YOLOv5x_b. During training a batch size of 56 is used for a maximum of 300 epochs. Backpropagation is performed using a learning rate of 0.01 with a stochastic gradient descent (SGD) optimizer (Robbins & Monro, 1951).

4.2 Symbol Detection Results

The YOLOv5 models are evaluated on 62 test images. Several key evaluation metrics are analyzed: precision, recall, intersection over union (IoU), mean average precision (mAP) at an IoU threshold of 0.50 (mAP@0.50), and mAP across IoU thresholds from 0.50 to 0.95 (mAP@0.50:0.95). The IoU measures the overlap between the predicted and ground truth bounding box. Precision measures the proportion of true positive detections out of all positive detections made by the model, indicating the accuracy of the model's predictions. On the other hand, recall represents the proportion of actual gradient symbols correctly identified by the models, measuring the model's ability to capture all instances of the target object. mAP@0.50 is a metric that enables the evaluation of the model's precision on average when there is at least a 50% IoU with the ground truth bounding boxes. In simpler terms, mAP@0.50 allows the assessment of how well the model performs in accurately detecting and localizing the gradient symbol, even when there is a moderate level of overlap between the predicted bounding boxes and the actual objects in the images. mAP@0.50:0.95 offers a more comprehensive evaluation by considering a range of IoU thresholds, enabling a better understanding of the model's performance across different levels of overlap. Since the gradient symbols are relatively small, this study considers an IoU of 50% sufficient.

The test results of different trained YOLOv5 models are shown in Table 2. It can be observed that the models achieve high precision scores, indicating their capability to accurately detect the gradient symbol in the real image dataset. Moreover, the models show varying levels of recall. YOLOv5m archives the highest recall score of 0.957, while YOLOv5l scores the lowest value of 0.882. Overall, the models successfully identify the gradient symbols but with some variation in recall performance.

Table 2: Gradient detection results for different models. The bold fonts indicate the best results.

	YOLOv5m	YOLOv5l	YOLOv5x	YOLOv5m _b	YOLOv5l_b	YOLOv5x_b
Precision	0.998	**1**	0.984	**1**	0.999	0.999
Recall	**0.957**	0.882	0.906	0.913	0.942	**0.957**
$mAP^{IoU}_{0.50}$	0.965	0.942	0.966	0.958	**0.977**	0.976
$mAP^{IoU}_{0.50:0.95}$	0.878	0.865	0.882	0.874	0.89	**0.894**

For the mAP@0.50 all models demonstrate strong performance. YOLOv5l_b achieves the highest mAP@0.50 of 0.977, followed closely by YOLOv5x_b with 0.976. YOLOv5l achieves the lowest mAP@0.50 score of 0.942. Considering the mAP@0.50:0.95 all models have consistently high scores. YOLOv5x_b achieves the highest score of 0.894, closely followed by YOLOv5l_b with 0.89. YOLOv5l shows the lowest mAP@0.50:0.95 score of 0.865. Overall, the models indicate a good performance across the range of IoU thresholds. Considering the detection speed and mAP@0.50 performance YOLOv5l_b is selected as the best model for this application. Some detection results of gradient symbols are presented in Fig. 6.

4.3 Overall Pipeline Results

The models successfully detect the symbols despite variations such as rotation and partial view. To assess the performance of the overall pipeline, it is tested on four real longitudinal views, each containing multiple gradient symbols. To evaluate the OCR accuracy, a character-level analysis is performed. The recognized characters extracted by EasyOCR are compared to the expected gradient parameters associated with each drawing. The accuracy is then calculated by determining the percentage of correctly recognized parameters relative to the total number of parameters present.

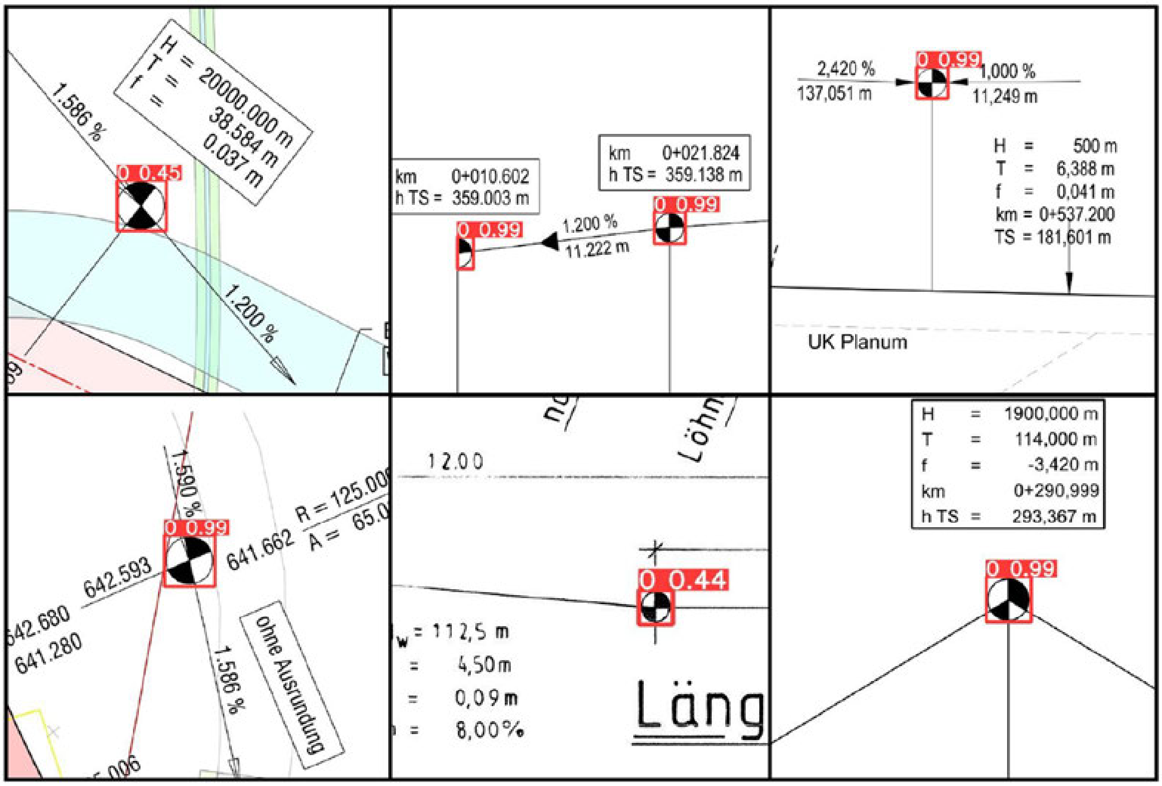

Fig. 6: Example results of gradient symbol detection.

The evaluation results reveal an overall accuracy of 70%. This shows that the pipeline can successfully extract gradient parameters from most of the drawings. However, there is room for improvement, especially in cases where parameter recognition becomes difficult due to variations in fonts and image quality.

5. DISCUSSION & CONCLUSION

The results of this study demonstrate the effectiveness of the proposed multistage pipeline for automatically extracting bridge gradient information from pixel-based construction drawings using deep learning techniques. The YOLOv5 models trained on different datasets showed high precision scores on the test dataset, indicating their capability to detect gradient symbols accurately. The results indicate that training the models on the synthetic dataset is beneficial to overcome a lack of data. The addition of background images has improved the overall performance of the models.

The evaluation metrics, including mAP@0.50 and mAP@0.50:0.95, revealed strong performance across all models. Notably, YOLOv5l_b achieved the highest mAP@0.50 score with 98%, making it the most suitable model for this application considering detection speed and accuracy. The detection results of gradient symbols further illustrate the pipeline's ability to successfully identify symbols despite variations in rotation and partial views. The pipeline's overall performance in extracting gradient parameters from real bridge drawings is promising, with an OCR accuracy of approximately 70%. However, there is still room for improvement, especially in cases with challenging text recognition due to varying fonts, and image quality.

In conclusion, the proposed pipeline presents an effective approach for the retro-digitization of existing bridges, significantly reducing the time and effort required for this crucial task. The successful extraction of gradient information from construction drawings holds great potential for improving bridge asset management and maintenance planning. For future research, fine-tuning, and optimization of the OCR component could further enhance accuracy and pave the way for broader applications.

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PREDICTING MENTAL WORKLOAD OF USING EXOSKELETONS FOR CONSTRUCTION WORK: A DEEP LEARNING APPROACH

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ABSTRACT: *Exoskeletons are gaining attention as a potential solution for addressing low back injury in the construction industry. However, use of active back-support exoskeletons in construction can trigger unintended consequences which could increase mental workload of users while working with exoskeletons. Prolonged increase in mental workload could impact workers' wellbeing and productivity. Prediction of mental workload during exoskeleton-use could inform strategies to mitigate the triggers. This study investigates a machine-learning framework for predicting mental workload of workers while using active back-support exoskeletons for construction work. Laboratory experiments were conducted wherein Electroencephalography (EEG) data were collected from participants wearing active back-support exoskeletons to perform flooring task. The EEG data underwent preprocessing, including band filtering, notch filtering, and independent component analysis, to remove artifacts and ensure data quality. A regression-based Long Short-Term Memory network was trained to forecast future time steps of the processed EEG data. The performance of the network was evaluated using root mean square error (RMSE) and r-squared (R^2). A RMSE of 0.1527 and R^2 of 0.9665 indicating good fit and strong correlation, respectively, were observed between the predicted and actual EEG data. Results of the comparison between the actual and predicted mental workload also show strong correction with an R^2 of 0.8692. The findings motivate research directions into real-time monitoring of mental workload of workers during exoskeleton-use. The study has significant implications for stakeholders, enabling them to gain a deeper understanding of the impact of mental workload while using exoskeletons thereby providing opportunities for mitigation.*

KEYWORDS: *Work-related musculoskeletal disorders, Exoskeleton, Mental workload, Electroencephalogram, Long Short-Term Memory, Flooring task.*

1. INTRODUCTION

The prevalence of work-related musculoskeletal disorders (WMSDs) among the construction workforce is a growing concern in the construction industry. The US Bureau of Labor Statistics reports that workers in the construction industry are 1.23 times more likely to sustain WMSDs compared with workers in other industry sectors (BLS, 2020). The same report explains that the back is the one of the most affected body parts. Construction workers, such as floor layers, suffer from back injuries at 1.7 times workers in other industry sectors. For example, floor layers experience back injuries at the rate 22.5 MSDs per 10,000 full-time workers, and this has been known to result in an average of 26 days' work absence. Exoskeletons are increasingly being perceived as a solution to WMSDs. Exoskeletons, such as back-support exoskeletons, are wearable devices designed to support or augment users' back while performing work (Gonsalves et al., 2023; Ogunseiju et al., 2022). Exoskeletons are classified as passive and active depending on their mode of augmentation. Passive back-support exoskeleton, while less costly than active back-support exoskeletons, provide support to the back using dampers and springs. Whereas active back-support exoskeletons provide support to the back using electrical motors – this makes active back-support exoskeletons bulkier. These devices have been shown to reduce risks factors of back injuries by reducing muscle activity (Theurel et al., 2018), range of motion (Cumplido-Trasmonte et al., 2023), body discomfort (Gonsalves et al., 2021; Kim et al., 2019), and rate of exertion (Alemi et al., 2020; Baltrusch et al., 2021). Despite these benefits, studies have shown that exoskeleton-use in construction can trigger difficulty working in confined spaces (Nussbaum et al., 2019), fall risks due to the weight of the device (Alabdulkarim et al., 2019; Kim et al., 2019; Massardi et al., 2023), discomfort to body parts (Gonsalves et al., 2023; Gonsalves et al., 2021), restrictions in movement (Fox et al., 2020; Poliero et al., 2020), catch and snag risks (de Looze et al., 2016; Kim et al., 2019), and thermal discomfort (Liu et al., 2021). The devices could also be challenging to adjust to fit (Gonsalves et al., 2023; Gorgey, 2018). Moreover, unequal loading and balancing of body parts due to improper adjustment can cause users to be more aware of the device than their task and surrounding, which could increase workers' mental workload (Bequette et al., 2020; Marchand et al., 2021).

Prolonged increase in mental workload can result in distraction, emotional distress, anxiety, and stress, which have downstream implication on workers' overall well-being and performance. Real-time monitoring of workers' mental workload during exoskeleton-use could inform strategies to reduce the triggers. However, scarce efforts

Referee List (DOI: 10.36253/fup_referee_list)
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Abiola Akanmu, Adedeji Afolabi, Akinwale Okunola, *Predicting Mental Workload of Using Exoskeletons for Construction Work: A Deep Learning Approach,* pp. 691-700, DOI 10.36253/979-12-215-0289-3.69

have been made to investigate models for predicting workers' mental workload during exoskeleton-use. Electroencephalogram (EEG) can be used to measure brain activity corresponding to mental workload. EEG signals are widely used for inferring mental workload, due to the high temporal resolution, convenience, and cost-effectiveness of the supporting devices. Machine learning techniques, particularly deep learning, provides opportunities for extracting insightful features from EEG data that could be used for predicting mental workload. Long Short-Term Memory network, a variant of recurrent neural network, can learn long-term dependencies between time steps of data and predict future time-series sequences of the data. Long Short-Term Memory (LSTM) network has been used for sequential learning tasks like construction equipment activity analysis (Hernandez et al., 2019), construction workers' safety harness usage (Guo et al., 2023), mixed reality learning environment (Ogunseiju et al., 2023) and, fatigue detection and early warning system (Liu et al., 2020) that need historical time-series data in the decision-making process. Therefore, this study investigates the extent to which workers' mental workload due to exoskeleton-use can be predicted from EEG data using Long Short-Term Memory network. Using a case-study of a flooring task, this paper presents a comparison of the actual and predicted mental workload due to performing work with an active back-support exoskeleton. The results of this study contribute to scarce knowledge on the unintended consequences of using wearable devices such as exoskeletons for construction work.

2. BACKGROUND

2.1 Mental Workload Evaluation with EEG

Mental workload are the mental resources required for task execution (Chen et al., 2017). A previous study (Fan & Smith, 2017) has shown that mental workload is associated with task demand and performance. Mastropietro et al. (2023) showed that low mental workload (underload) and high mental workload (overload) can negatively affect the task being executed leading to increase in rate incidence of errors. Chen et al. (2016) opined that when a person places too much attention on a task, the individual has less attention to focus on other stimuli. In the context of this study, exoskeleton-use may demand attention, thereby reducing the mental resources that may be required for the task or being aware of the user's surrounding to prevent fall risks, and catch and snag risks (Gonsalves et al., 2023; Zhu et al., 2021). These risks can impact the mental workload resulting in exoskeleton users being stressed or distracted, thus retarding their productivity and safety. This makes prediction of mental workload a major interest in ergonomics (Young et al., 2015). Over the years, subjective and objective methods have been employed to infer mental workload. Subjective methods include the use of questionnaires such as NASA Task Load Index and Subjective Workload Assessment Technique. On the other hand, objective methods include the use of data collection instruments such as functional magnetic resonance imaging-fMRI, and electroencephalography (Ryu & Myung, 2005). However, EEG has been touted as one of the most suitable devices for measuring brain activities to infer mental workload (Chen et al., 2016; Qin & Bulbul, 2023).

Borghini et al. (2014) estimates mental workload using theta-to-alpha brain waves ratio from EEG data. Similarly, another study (Missonnier et al., 2006) indicated that using EEG signals, an increase in mental workload is noticed when there is a decrease in alpha brain waves (8-13Hz) and increase in the theta brain waves (4-8Hz) during the execution of specific tasks. In the construction industry context, EEG has been used in some studies (Chen et al., 2016; Chen et al., 2017; Qin & Bulbul, 2023; Yang et al., 2023) to estimate mental workload. For instance, EEG was used to estimate the mental workload of construction workers to on-site safety conditions (Chen et al., 2016). Engagement index, time–frequency indicator in EEG, was used to assess the mental workload of workers when exposed to construction vulnerabilities. Chen et al. (2017) used EEG approach to measure task mental load of construction workers based on the power spectral densities of major frequency bands. In addition, the effect of distractions in construction work zones on drivers' mental workload was measured using EEG (Yang et al., 2023). Despite these efforts and unintended consequences of exoskeletons, there are scarce studies on predicting mental workload due to exoskeleton-use on construction sites.

2.2 Machine Learning for Mental Workload Prediction

With machine learning techniques, EEG data can be transformed into frequency domain representations which can enable extraction of brain rhythms. For instance, Jebelli et al. (2018a) used support vector machine, a supervised machine learning technique, to classify stress levels of construction workers. However, the use of supervised learning technique requires hand-crafting of features which could be labor-intensive and may be insufficient to support real-time monitoring of mental workload (Wang et al., 2023). Deep learning techniques, such as convolutional neural networks (CNN), have been used to extract intrinsic features from time-series data for recognizing occupational stress, fatigue and mental workload (Jebelli et al., 2019; Mehmood et al., 2023; Qin & Bulbul, 2023). Recurrent neural network, a class of CNN, is widely used for forecasting time-series data such as brain activity. Recurrent neural network, such as Long Short-Term Memory (LSTM), has been noted to perform better in learning time-series data due to its high prediction accuracy and ability to overcome problems of overfitting (Wang et al., 2020). Furthermore, LSTM can solve the problem of gradient exploding and vanishing when processing large sequential data (Hochreiter & Schmidhuber, 1997). Jaiswal et al. (2023) noted that LSTM model performed better than other models in predicting cognitive fatigue. Moreover, in their study, LSTM eliminated the need for extensive data preprocessing and feature extraction which could have resulted in loss of useful information in EEG data. Also, Liu et al. (2022) used LSTM for detecting fatigue of drivers. In construction, Qin and Bulbul (2023) used LSTM for predicting the mental workload of workers while using augmented reality head-mounted display for construction assembly. Despite these possibilities, limited studies have harnessed LSTM for predicting mental workload associated with exoskeleton-use for construction work.

3. METHODOLOGY

This section, including Figure 1, describes the procedure employed to achieve the objective of the study including the experimental design to collect brain activity of participants performing flooring task with an exoskeleton, preprocessing of the brain activity data, and prediction of mental workload with the data.

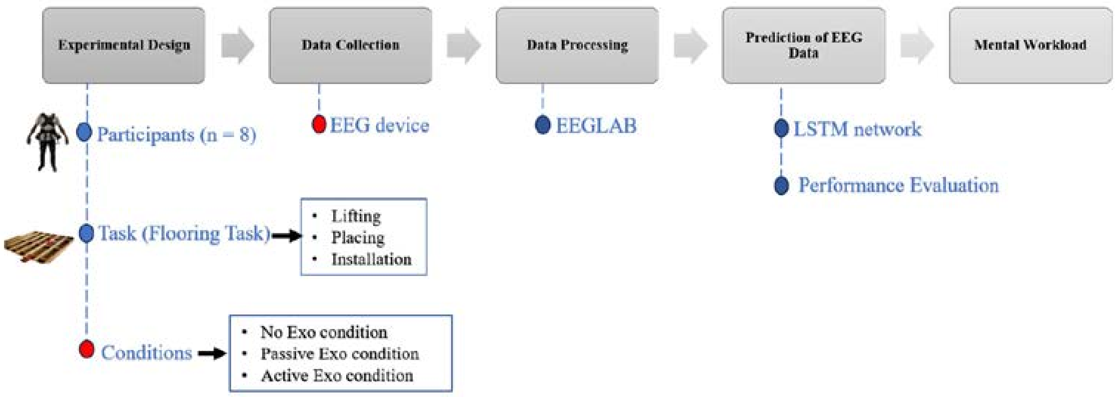

Fig. 1: Overview of Methodology.

3.1 Experimental Design and Data Collection

Eight male graduate students (n = 8) where recruited to perform a flooring task with an active exoskeleton. Similar sample sizes have been used by previous studies (Wei et al., 2020). None of the participants reported any prior musculoskeletal injury that would impact their participation in the study. The active exoskeleton used for the study is the Cray X shown in Figure 2. The Cray X, from German Bionic, weighs 7kg and can provide a lifting support of about 30kg. Cray X consists of a frame and strap pads of different sizes for the legs, chest, shoulders, and waist. The frame includes a 40V battery and motor. The exoskeleton provides different levels of support for bending, lifting, placing, and walking.

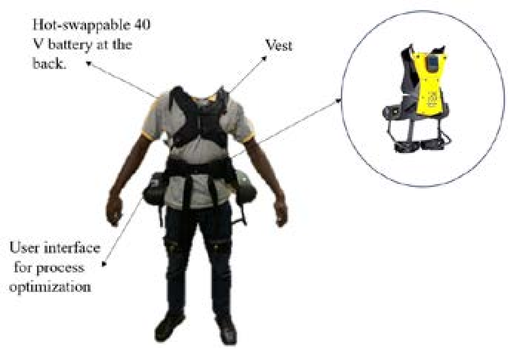

Fig. 2: Active (CrayX) back-support exoskeleton.

The flooring task involved lifting, placing and installing 20 floor tiles in each bay of a wooden frame comprising of six bays. Each bay can fit 20 floor tiles (see Figure 3). The participants were asked to lift and place 20 timber tiles (10kg) beside each bay, and subsequently install the stacked tiles in each bay. Each tile weighs 0.5kg. A cycle of flooring task includes lifting, placing, and installation of the timber floor tiles (20) in each bay. The task comprises of six cycles given that the participants installed the tiles in six bays.

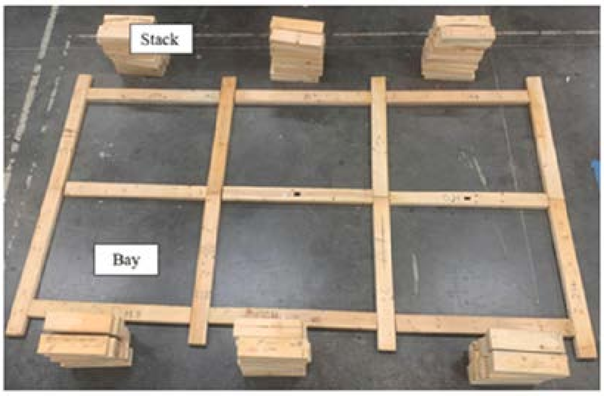

Fig. 3: Experimental layout of the simulated flooring task.

Prior to commencing the tasks, the participants received instructions on how to perform the task. The participants performed the aforementioned flooring task with an active exoskeleton. During these conditions, the participants wore an EEG cap. The EEG device records electrical activity of the brain through contact between electrodes embedded in various portions of the cap and the scalp. The brain produces electrical signals of brain waves at different frequencies such as delta (0.5-4 Hz), theta (4-8 Hz), alpha (8-13Hz), beta (13-30Hz), and gamma (>30Hz) (Chen et al., 2023). The delta, theta, alpha, beta and gamma bands correspond to deep sleep, powered thinking, alertness, concentration, and attentional processing, high mental activity, and information processing respectively (Ke et al., 2021). This study utilized a 14-channel EEG device measuring brain activity at 256Hz.

3.2 Data Preprocessing

EEG data are susceptible to contamination from intrinsic and extrinsic artifacts, particularly when subjects are engaged in physical activities like construction work (Jebelli et al., 2018b). These artifacts impact the quality of the signal. Intrinsic artifacts are triggered by movements such as eye blinking and muscle movement, while extrinsic artifacts are caused by external influences such as noise from wires and electrode popping. This study used the framework proposed by Jebelli et al. (2018b) to reduce the artifacts in the EEG data obtained from the simulated task. The EEG data were fed into EEGLAB, a MATLAB toolbox for processing physiological data. The extrinsic artifacts were removed using a Bandpass filter with cut-off frequencies of 0.5 and 65 Hz (Jebelli et al., 2018b). Another extrinsic artifact due to noise from wires was removed using a notch filter applied at a frequency of 60Hz. The intrinsic artifacts were removed using independent component analysis (ICA) (Mantini et al., 2008). The EEG data was decomposed using Extended Infomax method into 14 components, representing the 14 channels of the EEG device, and displayed using a scalp heatmap (Frølich & Dowding, 2018). Preprocessed data from eight channels (i.e., AF3, F3, P7, O1, O2, P8, F4, and AF4) were utilized for this study. The data points from the channels were split into training, validation, and testing, accounting for 70%, 10%, and 20% respectively.

3.3 Prediction of EEG Data

3.3.1 Long Short-Term Memory network

LSTM network, deep learning artificial recurrent neural network variant (RNN), was leveraged in this study to forecast subsequent values of the preprocessed EEG data. LSTM takes cognizance of the changes that could occur as the user gets used to the use of the device over time. LSTM neural network processes data by iterating over current time steps and retaining useful information to help with the processing of new data points. The regression LSTM neural network consists of four layers: an input layer, the LSTM layer, the fully connected layer and a regression layer. The input layer accepts the input time-series data and transfers this to the LSTM layer. The LSTM layer comprises of a cell, an entry gate, an exit gate, and a forget gate. The cell stores long-term time-series data and uses the gates to control flow of the data within and out of the cell. The forget gate decides which information should be ignored in the cell. The LSTM layer comprises of 128 hidden units. The number of hidden units determines how much information or data is learned by the layer. More hidden units could result in better results but are more likely to result to overfitting to the training data. The fully connected layer does the discriminative learning in the LSTM network. It learns weights that can identify features in the training data. The regression layer determines the performance metrics needed for the prediction task. The LSTM neural network is trained with a time-series sequence of EEG data, where the outputs are EEG values of subsequent time steps. To prevent overfitting and divergence of the training, the predictors and targets were normalized to zero mean and unit variance (Jebelli et al., 2018b). Hyperparameters have a significant impact on the performance of models. The network was trained with the Adam optimizer, an extension of stochastic gradient descent. In addition, 200 epochs, as well as a learning rate of 0.001 was used.

3.3.2 Performance evaluation

The performance of the LSTM model was evaluated using the Root Mean Square Error and R-squared. Root Mean Square Error (RMSE) is a standard statistical metric for computing accuracy. RMSE is generally used to evaluate the difference between the actual and predicted value from the model. RMSE is determined via equation 1, where A_i and P_i are the actual and predicted EEG datasets respectively, and n is the number of EEG datasets. The lower the RMSE, the better a model would fit a dataset. The R-Squared (R^2) which describes the variance in the response of a regression model, was computed following Renaud and Victoria-Feser (2010). The R^2 value ranges from 0 to 1. The higher the R^2 value, the better a model fits a dataset.

$$RMSE = \sqrt{\sum (P_i - A_i)^2 / n} \quad (1)$$

3.4 Mental Workload

The pre-processed EEG data (from Section 3.2) and the predicted EEG data from Section 3.3.1 were decomposed into frequency components to determine the power spectra of the data using Welch (1967)'s approach. The approach uses fast Fourier transformation with a Hamming window to determine the power spectral density of the EEG data. The relative band power of the windowed or segmented data in theta and alpha frequency bands were determined. Xing et al. (2020) mentioned that theta and/or alpha power are suitable indicators of mental workload. The mental workload of each segment was determined by dividing the absolute power in the theta band with the absolute power in the alpha band. The approximate spectral limits of these frequency bands are 4–8 Hz (theta) and 8–14 Hz (Simon et al., 2011).

4. RESULTS AND DISCUSSION

4.1 Performance of the LSTM Model for Each Channel

Table 1 shows the RMSE and R^2 scores for the EEG channels of one of the test participants. The RMSE values are less than 0.3 with the P7 and O1 channels having the lowest prediction errors. A previous study has indicated that a RMSE value closer to zero gives a better predictive power (Miyamoto et al., 2022). Similarly, the low RMSE in this study shows the high predictive power of the LSTM network in predicting mental workload. The R^2 scores of the channels are more than 0.9 which indicates close alignment or similarity between the predicted and actual EEG values.

Table 1: RMSE and R^2 scores for all the EEG channels.

	AF3	F3	P7	O1	O2	P8	F4	AF4	Average
RMSE	0.1174	0.1404	0.0772	0.0975	0.1700	0.1876	0.2090	0.2225	0.1527
R^2	0.9061	0.9144	0.992	0.9899	0.9941	0.9832	0.9755	0.9771	0.9665

4.2 Mental workload

4.2.1 Comparison between Predicted and Actual PSD

Figure 4 shows the predicted and actual power spectral density of the AF3 and O2 channels for the data of one of the test participants. The predicted and actual data are the red and blue lines respectively. At less than 45Hz, both figures show some consistency between the predicted and actual PSD values.

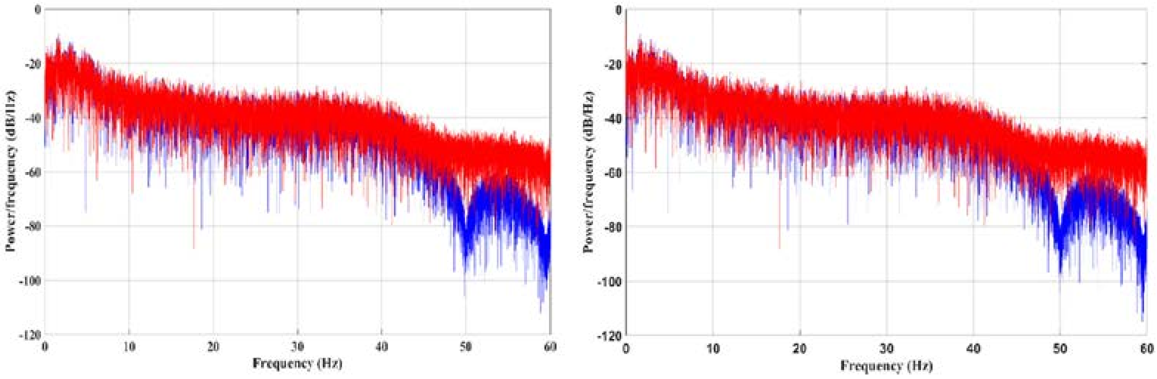

Fig. 4: Predicted and actual power spectral density of the AF3 channel (left) and O2 channel (right).

4.2.2 Mental workload

The extent to which mental workload due to exoskeleton-use can be predicted is illustrated in the scatter diagram in Figure 5. The plot has a R^2 score of 0.8692 indicating a strong correlation between the predicted and the actual mental workload. A previous study (Coulibaly & Baldwin, 2005) has shown that R^2 score between 0.8-0.9 is termed acceptable. The result suggest that it is possible to predict mental workload during exoskeleton-use for construction work. Previous studies have corroborated the assertion that mental workload can be predicted (Borghini et al., 2014; Missonnier et al., 2006; Qin & Bulbul, 2023).

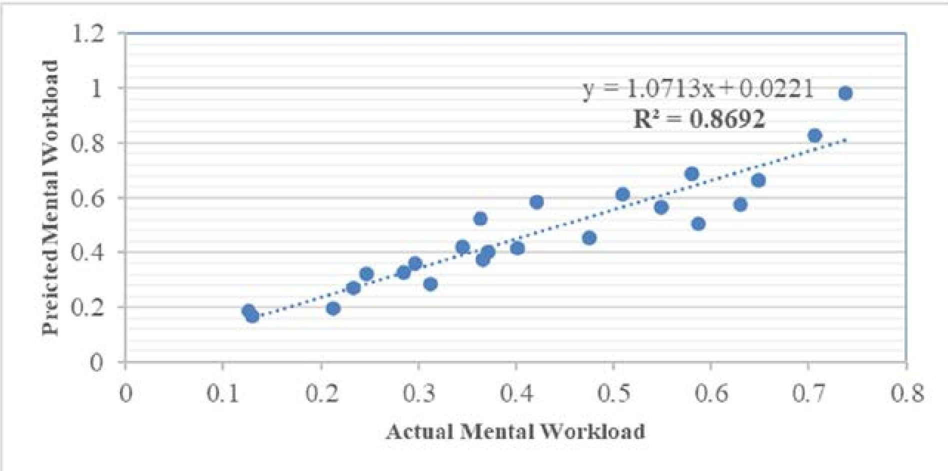

Fig. 5: Comparison of predicted and actual values of the mental workload.

5. CONCLUSIONS, LIMITATIONS AND FUTURE WORK

This study presents the extent to which mental workload due to exoskeleton-use can be predicted from EEG data using Long Short-Term Memory network. EEG data were obtained from an experimental study where participants performed flooring task with an active back-support exoskeleton. The data were preprocessed and trained with the Long Short-Term Memory network to identify unique features for forecasting brain activity. A comparison of the actual and predicted brain activity data indicates close consistency, with average root mean square error and r-squared of 0.1527 and 0.9665 respectively. Similar trends were observed in the comparisons of the predicted and actual power spectrums and mental workload. The results of this study contribute to scarce literature on the impact of unintended consequences of using exoskeletons for construction work. The study motivates investigations into the use of machine learning for real-time performance predictions of technological innovations on construction projects. The study may have been limited due to the sample size of eight participants which was used to train the deep learning algorithm. Training data from a larger sample could improve the performance of the model and its generalizability. This would be achieved by using time-series based data augmentation techniques such as scaling, permutation and generative adversarial networks. Future studies can compare the mental workload of no exoskeleton and active exoskeleton conditions. In addition, further investigation on the suitability of other deep learning networks to identify the most suitable networks for predicting mental workload can be carried out. Besides, future studies can support mental workload prediction with the understanding of the risks influencing mental workload using subjective feedback that describes user experience of exoskeletons.

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UTILIZING 360-DEGREE IMAGES FOR SYNTHETIC DATA GENERATION IN CONSTRUCTION SCENARIOS

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ABSTRACT: *Computer vision-based safety monitoring requires machine learning models trained on generalized datasets covering various viewpoints, surface properties, and lighting conditions. However, capturing high-quality and extensive datasets for some construction scenarios is challenging at real job sites due to the risky nature of construction scenarios. Previous methods have proposed synthetic data generation techniques involving 2D background randomization with virtual objects in game-based engines. While there has been extensive work on utilizing 360-degree images for various purposes, no study has yet employed 360-degree images for generating synthetic data specifically tailored for construction sites. To improve the synthetic data generation process, this study proposes a 360-degree images-based synthetic data generation approach using Unity 3D game engine. The approach efficiently generates a sizable dataset with better dimensions and scaling, encompassing a range of camera positions with randomized lighting intensities. To check the effectiveness of our proposed method, we conducted a subjective evaluation, considering three key factors: object positioning, scaling in terms of object respective size, and the overall size of the generated dataset. The synthesized images illustrate the visual improvement in all three factors. By offering an improved data generation method for training safety-focused computer vision models, this research has the potential to significantly enhance the automation of the construction safety monitoring process, and hence, this method can bring substantial benefits to the construction industry by improving operational efficiency and reinforcing safety measures for workers.*

KEYWORDS: *360-Degree Images, Computer Vision, Synthetic Data Generation, Game Engine, Object Detection, Construction Safety Monitoring*

1. INTRODUCTION

Effectively monitoring construction sites in real-time demands robust computer vision (CV) models trained on diverse datasets capturing different viewpoints, surface properties, and lighting conditions (Li et al., 2022; Sami Ur Rehman et al., 2022). This diversity ensures accurate and adaptable surveillance for improved safety and efficiency. However, obtaining such extensive and high-quality datasets poses significant challenges. Furthermore, addressing the complexities of dynamic construction environments with numerous elements and rapidly changing conditions is a recognized challenge. To address these issues, the utilization of smart devices for automated progress and real-time construction monitoring through object detection technology and positional data presents a rapid and precise solution (Rho et al., 2020).

Previous methods attempted to address this issue propose synthetic data generation techniques by introducing 2D background randomization with virtual objects in game-based engines (Zhang et al., 2022). While these techniques have shown promise in controlled settings, they still exhibit shortcomings in dynamic construction work environments (Lee et al., 2022). This limitation might arise from the complexity of recreating the intricate interactions among dynamic elements and the complex spatial relationships found in construction sites. Capturing the subtle aspects of depth perception and object occlusion, which are essential for precise object detection, can pose a challenge when working with synthetic datasets (Choi & Pyun, 2021).

This study presents a pioneering method utilizing 360-degree images to craft synthetic data, leveraging the Unity 3D game engine, to comprehensively address these challenges. By adopting this approach, we aim to bridge the gap between synthetic and real-world data, enabling effective training of CV models for construction scenarios. The proposed method efficiently generates a sizable dataset with better dimensions and scaling, encompassing a range of camera positions with day and night lighting intensities. This not only facilitates improved object detection but also opens avenues for applications in construction progress monitoring and site safety analysis. To validate the proposed method, we conducted a thorough analysis, encompassing the examination of three crucial factors: Object Position, objects' size scaling, and dataset size.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Aqsa Sabir, Rahat Hussain, Syed Farhan Alam Zaidi, Akeem Pedro, Mehrtash Soltani, Dongmin Lee, Chansik Park, *Utilizing 360-Degree Images for Synthetic Data Generation in Construction Scenarios,* pp. 701-710, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.70

Object positioning factor scrutinizes the precision with which objects are localized within the synthetic data. It involves a meticulous assessment of the alignment and placement of objects in relation to their real-world counterparts. Higher accuracy in object positioning indicates closer adherence to reality, crucial for applications demanding precise spatial understanding. Object size scaling refers to the scale at which objects are represented within synthetic data, a critical dimension. This factor entails a meticulous examination of whether the size relationships between objects are faithfully replicated. Accurate scaling ensures that the synthetic data mirrors the real-world environment, influencing tasks where object proportions are of paramount importance. Dataset size describes the magnitude of the dataset generated through the proposed technique, an instrumental metric in its efficacy. A larger dataset not only provides a more comprehensive representation of the construction scenario but also potentially enhances the performance of machine learning models. It enables a broader spectrum of scenarios to be captured, invaluable in training robust computer vision models.

Following the introduction and background section, which provide a thorough overview of the research problem, Section 2 offers an extensive literature review. Section 3 then elaborates on the proposed synthetic data generation method. Section 4 performs a comparative analysis between the proposed approach and conventional methodologies. Finally, the paper concludes by summarizing its contributions and delineating potential avenues for future research.

2. LITERATURE REVIEW

The construction industry encounters formidable challenges in procuring authentic image data, largely stemming from the perilous and dynamic nature of construction sites. In response, synthetic data generated through computer graphics emerges as a promising and cost-effective solution for training machine learning models in the construction sector. This approach proves especially conducive to tasks such as site monitoring, defect detection, and material classification, endowing models with the capability to derive invaluable insights. Consequently, this enhances the efficiency and efficacy of construction processes and outcomes in practical, real-world scenarios.

A suite of techniques, including computer graphics, data simulation, data augmentation, generative adversarial networks (GANs), and synthetic-to-real transfer learning, collectively contribute to the generation of synthetic datasets. Among these, computer graphics entails the creation of three-dimensional (3D) models of objects and scenes through specialized software platforms like Blender, Autodesk 3ds Max, Maya, or the Unity Game Engine. This process culminates in the rendering of these models to generate two-dimensional (2D) images (Frolov et al., 2022). The advantage lies in the controlled environment it affords for data generation, enabling the creation of bespoke datasets with predefined attributes, including controlled variations in lighting, camera angles, or object orientations (Oh et al., 2021; Wong et al., 2019). Data simulation, on the other hand, involves the emulation of the underlying data generation processes and interrelationships between variables. This endeavor yields synthetic images that closely mimic the appearance and geometric characteristics of their real-world counterparts. Concurrently, generative adversarial networks (GANs) represent a neural network architecture comprising a generator network and a discriminator network. This setup empowers the generator to create novel images while the discriminator distinguishes between generated and authentic images, culminating in adversarial training. Moreover, synthetic-to-real transfer learning encompasses the training of a model on synthetic data, followed by fine-tuning on authentic data. This iterative process engenders synthetic data that closely approximates real-world data. These methodologies, whether utilized in isolation or synergy, facilitate the generation of expansive and diverse synthetic datasets for training and assessing machine learning models within the construction domain.

In 2015, Soltani et al. conducted pioneering work in synthetic data generation for excavation tasks, utilizing Autodesk 3ds Max and Google SketchUp in conjunction with Histogram of Gradient (HOG) transformations for precise segmentation (Soltani et al., 2016). Since then, a surge of studies, particularly post-2020, has significantly advanced this field. Neuhausen et al., Kim et al., and Tohidifar et al., turned to Blender software, leveraging its capabilities in constructing intricate 3D models of workers (J. Kim et al., 2022; Neuhausen et al., 2020; Tohidifar et al., 2022). Similarly, Kim et al. extended Blender's utility by creating synthetic images of scaffolds through the integration of point clouds (A. Kim et al., 2022). Barrera-Animas et al., introduced an innovative methodology that combines Blender-based synthetic image generation with automatic labeling, effectively surmounting limitations associated with separate processes (Barrera-Animas & Davila Delgado, 2023).

Wei et al. harnessed Building Information Modeling (BIM) software to create comprehensive 3D models of buildings at various stages of construction. These models were seamlessly integrated with Unreal Engine, facilitating the generation of a synthetic dataset exhibiting diverse light conditions and viewing perspectives (Wei & Akinci, 2022). Sutjaritvorakul et al. and Siu et al. capitalized on Unreal Engine's capabilities to generate images of workers and sewerage pipes, respectively, catering to object detection through closed-circuit television (CCTV) cameras (Siu et al., 2022; Sutjaritvorakul et al., 2020).

More recently, there has been a notable surge in the utilization of the Unity Perception package for synthetic data generation. Another study harnessed Unity Perception to intricately craft building facades in Koto City, employing manual annotation techniques involving polygons and bounding boxes (Zhang et al., 2022). Similarly, few more efforts towards generating datasets tailored for construction workers and excavation tasks, implemented bounding box auto-annotation methods (Assadzadeh et al., 2022; Lee et al., 2022). Notably, the Unity Perception package was initially introduced by Borkman et al. for synthetic dataset creation in computer vision applications (Borkman et al., 2021). This package emerged as an invaluable resource in generating expansive synthetic data sets for our machine learning models. Its rich array of features prompted us to explore its potential with 360-degree images within the construction domain. Noteworthy functionalities such as the Perception Camera and robust data labeling options facilitated the creation of a diverse and highly accurate dataset, crucial for training effective machine learning models. Indeed, earlier studies were constrained by their narrow focus and reliance on manual annotation methods, which limited their scalability and real-world applicability. Moreover, challenges in faithfully replicating dynamic construction environments remained unaddressed. This study pioneers 360-degree image and Unity 3D-based synthetic data generation for construction scenarios, overcoming challenges, and improving object detection for safety and monitoring.

3. METHODOLOGY

The research process outlined in this paper is delineated into five distinct stages, as illustrated in Figure 1. The research process began with Data Collection and Preprocessing, where real-world construction site imagery was gathered and prepared for further analysis. Subsequently, Virtual Construction Site Simulation was conducted to create a digital representation mirroring real-world scenarios. This simulation served as the foundation for generating annotated data through the integration of the Unity Perception package. The package's capabilities, including Perception Camera and data labeling options, played a pivotal role in producing a diverse and accurately annotated dataset. Finally, the Results and Evaluation section scrutinized the performance of the machine learning models trained on the synthetic data, providing valuable insights into their effectiveness in dynamic construction environments. Furthermore, Figure 2 illustrates the complete system architecture.

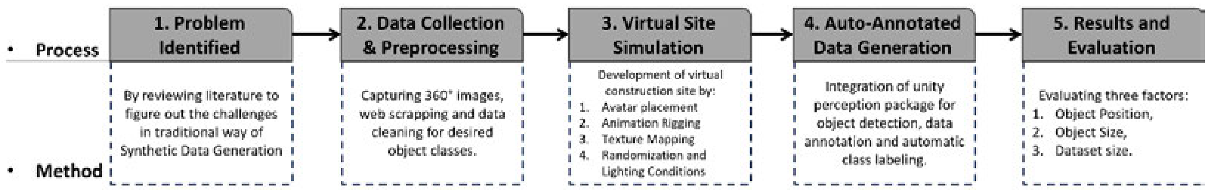

Fig 1: Research Process

3.1 Data collection and preprocessing

The initial phase of constructing our synthetic dataset involved the acquisition of authentic 360-degree images from real-world construction sites. This imperative task was accomplished through on-site visits to various construction locations, where we employed a Ricoh Theta V camera to capture high-fidelity images. A comprehensive set of approximately 49 shots was meticulously taken across three distinct sites. These captures were strategically dispersed across three distinct sites, a deliberate maneuver aimed at ensuring a panoramic representation of both indoor and outdoor contexts. This strategic diversity not only broadens the dataset's scope but also fortifies its ecological fidelity, essential for simulating real-world scenarios accurately.

To uphold the dataset's integrity and applicability, a discerning filtering process was meticulously implemented. This process entailed the deliberate exclusion of instances featuring the target classes or objects slated for subsequent annotation. Moreover, as a supplementary measure to bolster the dataset, an additional 20 images were judiciously selected from reputable online sources. These images underwent a rigorous refinement process, facilitated by Adobe Photoshop, a widely recognized image editing tool. This intervention was crucial in the removal of extraneous elements that might have inadvertently compromised the dataset's fidelity. This meticulous curation was necessitated by the publicly accessible nature of these images.

By rigorously adhering to these meticulous acquisition and preprocessing protocols, we established a robust foundation for the subsequent stages of annotation and synthetic data generation. This methodological rigor ensures that the dataset remains of the highest quality and relevance, serving as an indispensable resource for the accurate training and evaluation of our computer vision models in dynamic construction environments.

3.2 Virtual construction site simulation:

During this pivotal phase, the synthesis of virtual components was meticulously undertaken to construct a dynamic virtual construction site. This critical stage comprised four foundational elements, each of which played a significant role in enhancing the authenticity and diversity of the synthetic dataset. A situation as a case scenario where workers are actively engaged in ladder climbing was meticulously composed to clearly capture the real atmosphere of a construction site environment.

3.2.1 Avatar Placement:

The foundational step involved generating 3D avatars with distinct physical attributes and appearances through Ready Player Me. To augment avatar diversity, human parts from SketchFab were incorporated, with customization of attire and features. Avatars were tailored to emulate team members' characteristics using the Unity 3D avatar maker plugin, and adjustments to facial features and joints were made using Blender and Unity 3D. Six avatars were strategically positioned within the hollow cylinder structure. This included four male workers alternating between two ladders switching on/off at predetermined intervals. Helmets, a safety precaution, were optionally worn during simulation. Dataset diversity was amplified by introducing random alterations in clothing color, pattern, skin complexion, and hair shade. This amalgamation of diverse and realistic avatars not only diversifies the synthetic dataset but also augments its capacity to simulate a broad spectrum of personnel scenarios within a construction site environment.

3.2.2 Animation Rigging:

In the subsequent phase, a climbing animation was seamlessly integrated into the avatars within the unity game engine. A pre-existing climbing animation from Mixamo[1] was utilized and imported into the Unity engine. The animation was then rigged to the avatars, with meticulous adjustment of parameters to ensure perfect synchronization with the ladder model The seamless integration of climbing animations fortifies the dataset by providing a realistic representation of ladder-related actions. This, in turn, equips ML models with the proficiency to accurately identify and classify such actions within the construction site environment.

3.2.3 Texture Mapping:

The Texture Mapping phase was dedicated to seamlessly enveloping the 360-degree background images around the virtual cylinder. Distinct materials were assigned to each image, with meticulous organization within a designated folder named MaterialsBG in the Unity project. To infuse the synthetic data with variety, a script was implemented to randomly select materials from the MaterialsBG folder, generating a diverse array of image frames. This strategic process played a pivotal role in cultivating a truly immersive virtual environment. The judicious mapping of the 360-degree images onto the surface of the cylinder heightened the authenticity of the synthetic dataset, furnishing it with meticulously curated training data of superior quality for ML models.

3.2.4 Randomization and Lighting Conditions:

Dynamic lighting effects were harnessed to infuse our virtual construction site with an authentic and immersive ambiance. The Unity engine's built-in directional light was adeptly employed to replicate a spectrum of natural lighting conditions, spanning dawn, noon, afternoon, and night. A meticulously crafted script dynamically modulated the light intensity, mimicking the natural progression of light over time. This meticulous attention to lighting dynamics further fortified the efficacy of the synthetic dataset, as CV based techniques rely on precise lighting cues for accurate object identification and localization.

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[1] https://www.mixamo.com/#/

3.3 Generating annotated data through unity perception PACKAGE INTEGRATION:

The incorporation of the Unity Perception Package stands as a transformative stride in elevating the authenticity and intricacy of our synthetic dataset. This comprehensive toolset within the Unity environment streamlines the process of automatic labeling and annotation of objects based on pre-defined classes, a critical step for training computer vision models.

At the core of this integration lies the Camera Sensor component. This crucial element faithfully simulates the behavior of a real-world camera, capturing images from the scene with a level of fidelity that closely mirrors actual visual acquisition. This technical facet not only enriches the dataset's realism but also empowers our models to process images in a manner akin to their real-world counterparts. Complementing the Camera Sensor is the Labeler Component, an indispensable tool for training computer vision models. This component meticulously annotates objects within the scene, a vital step in providing the models with ground truth information for accurate object detection and classification. This facet significantly enhances the dataset's utility in training robust models capable of discerning and categorizing objects within complex construction environments. Moreover, the Renderer Component stands as another critical element in this integration. This component harnesses the Unity Perception Package's neural rendering pipeline to meticulously render the scene. By doing so, it imbues the generated images with a level of visual fidelity that is essential for training models to recognize and understand complex, real-world scenarios.

The Labeler Component acts like a foundation in the process of training computer vision models. It interfaces seamlessly with a predefined set of classes and automatically identifies objects within the scene, assigning them appropriate labels based on their class membership. This automated labeling process significantly amplifies the dataset's efficacy in training robust models capable of discerning and categorizing objects within the dynamic and intricate environments of construction sites. The Labeler Component operates in tandem with scripts written in C#, leveraging the Perception API provided by the package. These scripts access object information and apply labels to them based on their class. The API includes functions and methods that facilitate this automatic annotation process. Through the orchestrated interplay of the Labeler Component, Perception API, and scripts, our synthetic dataset gains a precise and detailed ground truth, indispensable for training computer vision models. This annotated data forms the cornerstone of our dataset, empowering our models in object detection and environmental perception tasks within the complex and safety-critical context of construction sites. Through the orchestrated interplay of the Labeler Component, Perception API, and scripts, our synthetic dataset gains a precise and detailed ground truth, indispensable for training computer vision models. This annotated data forms the cornerstone of our dataset, empowering our models in object detection and environmental perception tasks within the complex and safety-critical context of construction sites.

As a result of this integration, the Unity Perception Package generates several key JSON files alongside the image dataset. These files, including 'annotation_definitions.json', 'captures.json', 'metric_definitions.json', 'metrics.json', and 'sensors.json', hold crucial annotation data, capture details, metric definitions, recorded metrics, and sensor information respectively. They play a pivotal role in enriching our dataset for object detection model training and evaluation. The annotation_definitions.json file, for instance, provides detailed information about class labels and object attributes, while captures.json contains information regarding the captured scenes. These JSON files collectively form the backbone of our dataset, empowering our models with the necessary information to accurately perceive and interpret the dynamic construction environment.

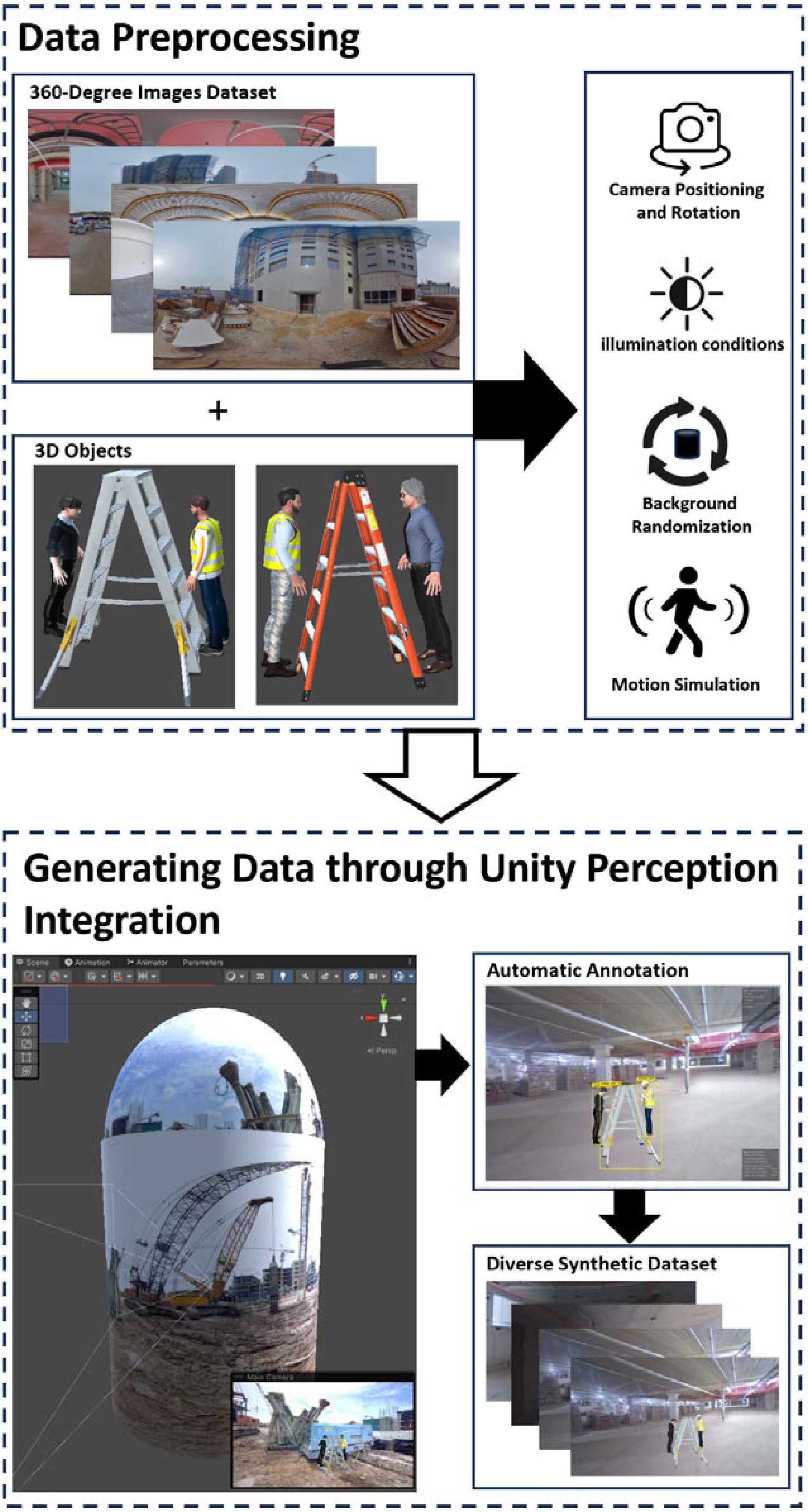

Fig 2: System Architecture explaining whole process of synthetic dataset generation.

4. RESULTS

The synthetic data generated through the proposed approach utilizing 360-degree images was focused on three critical factors: Object Position (Accuracy), Object Size (Scaling), and Dataset Size. The results from proposed techniques are shown in Figure 3.

4.1.1 Object Positioning:

Upon thorough examination, it became evident that the synthetic data derived from 360-degree images demonstrated excellent accuracy in object position determination. The comprehensive perspective offered by 360-degree images facilitated more precise object localization within the construction environment. This was particularly notable in instances where objects were positioned in close proximity or within complex spatial configurations. The enhanced depth perception afforded by the spherical perspective of 360-degree imagery played a pivotal role in accurately pinpointing object locations. Moreover, the capability to observe objects from diverse angles within a single image frame contributed to a deeper comprehension of their spatial relationships within the construction site. This heightened accuracy in object positioning is a critical advantage, especially in safety-critical environments where precise object localization is paramount for accident prevention and worker safety.

4.1.2 Object's Size Scaling:

One of the notable advantages of leveraging 360-degree images was the observed improvement in object size scaling. The spherical perspective offered by 360-degree imagery allowed for a more precise representation of object sizes in relation to their immediate surroundings because it encompassed a comprehensive view of the entire environment without the distortions. This panoramic view allowed for a faithful portrayal of how objects interacted within the construction site, aligning closely with their real-world proportions. This was especially pertinent when considering objects from varying angles or perspectives. The spherical view granted by 360-degree images mitigated distortions, ensuring that object sizes were accurately depicted regardless of the viewing angle. In contrast, data generated from 2D background images often grappled with limitations in faithfully representing object sizes, particularly when objects were viewed from non-standard angles. Additionally, the ability to view objects from multiple angles in a single image frame further contributed to this enhanced accuracy in size representation. This critical improvement in object size scaling with 360-degree imagery contributes significantly to the overall fidelity and accuracy of the synthetic dataset, ultimately enhancing the effectiveness of computer vision models in interpreting real-world construction scenarios.

4.1.3 Dataset Size:

The size of dataset played a pivotal role in influencing the performance of computer vision models. The use of 360-degree images facilitated the creation of a larger dataset. A significant contributor to this considerable dataset expansion is the unique capability of 360-degree images. A single 360-degree image can generate multiple frames, each offering different perspectives while maintaining consistent lighting and camera positions. This efficiency greatly enhances the adaptability and effectiveness of models in real-world construction site scenarios. The substantial dataset derived from 360-degree images significantly broadened the ability of models to generalize and make well-informed decisions across a wide range of construction site scenarios. Undoubtedly, this rich training data strengthened the robustness and competence of models, establishing it as a valuable tool for real-time construction site monitoring.

Fig 3: Results of the proposed approach.

5. DISCUSSION AND CONCLUSION

This study introduces a 360-degree image-based approach for generating synthetic data to train CV models for construction site safety monitoring. The 360-degree dataset excels in object positioning due to its ability to provide a comprehensive view of the construction site from multiple perspectives. This advantage is particularly valuable for precise object localization in complex spatial arrangements common in construction settings. Additionally, the spherical perspective inherent in 360-degree images ensures a more accurate representation of object sizes relative to their surroundings. This accuracy is crucial for effective monitoring in construction environments, as it aligns object proportions faithfully with real-world dimensions. Furthermore, the larger dataset size derived from 360-degree images offers extensive and diverse training data, enabling the model to generalize effectively across various construction scenarios. Unlike 2D images that produce only one synthetic image for one scenario, each 360-degree image can generate multiple synthetic images for one scenario.

The advantages of employing 360-degree images as the foundation for synthetic data generation are multifold. The all-encompassing view offered by 360-degree imagery allowed for a more holistic representation of the construction environment. This comprehensive perspective, combined with the ability to accurately depict object positions and sizes, resulted in a dataset that offered a remarkably realistic simulation of real-world scenarios.

It is important to acknowledge that while this approach demonstrates notable progress, it does have certain limitations. A limitation of using 360-degree imagery, versus prior 2D background images, is handling dynamic elements on construction sites. While offering a broad view, 360-degree images may introduce distortion, especially at the edges, impacting object detection accuracy, especially for peripheral objects. Addressing and correcting this distortion during data generation is crucial for precise computer vision model training. Future research aims to expand the dataset, explore advanced model architectures, and assess data efficacy through computer vision-based model training on actual construction sites. Integration of multimodal information, like combining imagery with LiDAR or other sensors, will enrich the dataset and enhance object detection accuracy. Furthermore, we will objectively measure the effectiveness of the proposed approach by conducting computer vision-based model training and comparing the results with the traditional method of generating synthetic data. This approach holds the potential to serve as a foundational framework for numerous industries, offering a blueprint for the modernization of their safe operations, thereby propelling safety standards and operational prowess to new heights on an international scale.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. NRF-2022R1A2B5B02002553) and the "National R&D Project for Smart Construction Technology (No.23SMIP-A158708-04)" funded by the Korea Agency for Infrastructure Technology Advancement under the Ministry of Land, Infrastructure and Transport, and managed by the Korea Expressway Corporation.

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MACHINE LEARNING-BASED CONSTRUCTION PLANNING AND FORECASTING MODEL

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ABSTRACT: *Construction planning and scheduling are crucial aspects of project management that require a lot of time and resources to manage effectively. Machine learning and artificial intelligence techniques have shown great potential in improving construction planning and scheduling by providing more accurate insights into project progress and forecasting. This paper proposed a machine learning model that utilizes regularly updated site data to generate predictions of quantity variances from the plan and enable a more accurate forecast of future progress based on historical data on concrete activities. Also, the outputs of this model can be used when creating a schedule for a new project. New schedules created with the help of this model will be more consistent and reliable due to its vast data pool and ability to generate realistic forecasts from this data. The model utilizes data from completed and other ongoing projects to generate insights and provide a more accurate and efficient construction planning and scheduling solution. Within the scope of this study, different attributes of concrete pouring activities of different projects and locations were used as input data for a machine learning process, and then, using this model on test data, the forecast concrete quantities were obtained. This model provides a more advanced solution than traditional project management tools by incorporating machine learning techniques while significantly improving construction planning, scheduling accuracy, and efficiency, leading to more successful projects and increased profitability for construction companies.*

KEYWORDS: *Machine Learning, Planning, Scheduling, Forecasting, Data Visualizing, Construction, Business Intelligence*

1. INTRODUCTION

Developing project schedules is critical to all projects, including engineering, manufacturing, construction, and others (Faghihi, Reinschmidt & Kang, 2014). Creating a reliable schedule and then updating and monitoring it as the project progresses is crucial for project management. A continuous data flow from the site is necessary to monitor project progress correctly. This process creates a vast amount of data. The construction industry deals with significant data from various disciplines throughout the life cycle of a facility (Bilal et al., 2016). Despite the abundance of data generated, its utilization in construction projects is often overlooked, resulting in a staggering amount of unused information. It is postulated that 96% of the data collected during construction projects goes unused (Snyder et al., 2018). In order to harness the potential of this unused data, various techniques such as statistics, machine learning, and artificial intelligence can be employed. Statistics are already commonly studied and applied within the construction sector. However, the importance of machine learning (ML), more generally, artificial intelligence (AI), is mostly overlooked and not being applied by companies as necessary, despite the studies on the matter.

Machine Learning applications have proven to outperform existing techniques, methods, and human decision-making on construction sites (Hammad et al., 2014). These methodologies offer valuable tools for further processing the data, enabling applications such as forecasting, risk analysis, labor allocation, and defect analysis. By leveraging these processes, construction professionals can unlock insights and optimize decision-making throughout the project lifecycle. Exploiting the power of ML data analytics tools can result in significant corporate benefits by enhancing the time performance of construction projects—regarded as one of the critical indicators of a successful project (Gondia et al., 2019). The most important part of construction project scheduling is the selection of resources (e.g., workforce, machines) and harmonizing their work (Jaskowski & Sobotka, 2006). This study aims to create more accurate forecasts for concrete pouring activities for effective planning, such as resource allocation in power plant projects. Often, project planners lack detailed drawings and necessary quantities at the beginning of the project. Even if such information is available initially, these quantities frequently change the project due to various factors. These factors may include unexpected soil features, inexperienced workforce, supplier delays, adverse weather conditions, or suboptimal planning. With the help of Machine Learning, correlations were sought between planned and at-completion quantities for data obtained from construction

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Ahmet Esat Keser, Onur Behzat Tokdemir, *Machine Learning-Based Construction Planning and Forecasting Model*, pp. 711-717, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.71

projects. Data was collected from various ongoing or completed projects a construction company undertook to accomplish this. This data served as valuable input for machine learning models, enabling us to obtain meaningful and actionable results.

2. MATERIAL AND METHODS

Firstly, data was anonymously collected from 4 different projects (all personal and company-related information was removed). The projects are power plants in the following locations:

- Tashkent, Uzbekistan,
- Ashgabat, Turkmenistan,
- Sulaymaniyah, Iraq (two projects).

The primary data was obtained from the SAP Database ("SAP: Enterprise Application Software," n.d.) of the company, which is updated weekly for every project. SAP export data consisted of detailed weekly progress of the projects. Another data source is the Oracle Primavera ("Primavera P6 Enterprise Project Portfolio Management," n.d.) database. The company database has detailed L3 Updated Schedules and Baselines for each project. These schedules can provide planned and at-completion durations and start/finish dates if needed. At the date of this study, one of the projects was completed, and the other two were still ongoing, so data until the latest data date (30.06.2023) was used even though some of the activities were not completed.

Firstly, concrete pouring activities were filtered. The projects and schedules were taken from the same company and created according to the same procedures. Thus, all concrete pouring activities' wording and coding format are the same, as shown in Table 1.

Table 1: Activity ID and Name Structure of the Schedules

Activity ID	Activity Name
BZC-U-C-UBE-1800	Excavation of Soil - Foundation Level - Control Building
BZC-U-C-UBE-1810	Filling & Compaction - Foundation Level - Control Building
BZC-U-C-UBE-1860	Lean Concrete Pouring - Foundation Level - Control Building
BZC-U-C-UBE-1820	Installation of Formwork - Foundation Level - Control Building
BZC-U-C-UBE-1830	Installation of Rebar - Foundation Level - Control Building
BZC-U-C-UBE-1840	Concrete Pouring - Foundation Level - Control Building
BZC-U-C-UBE-1870	Installation of Formwork for Column - Ground Floor - Control Building
BZC-U-C-UBE-1880	Installation of Rebar for Column - Ground Floor - Control Building
BZC-U-C-UBE-1890	Concrete Pouring for Column - Ground Floor - Control Building
BZC-U-C-UBE-2040	Installation of Formwork for Beam & SLCA - Ground Floor - Control Building
BZC-U-C-UBE-2050	Installation of Rebar for Beam & Slab - Ground Floor - Control Building
BZC-U-C-UBE-2060	Concrete Pouring for Beam & Slab - Ground Floor - Control Building

The wording format of the data is as follows;

"Activity Description" – Level/Element – Building

The concrete activities start with "Concrete Pouring" as Activity Description. After the activity description, another attribute can be "level" or "element": foundation, column, slab, pedestal, wall, or trench. Moreover, there are different buildings of different sizes and floors. However, these projects mostly have concrete structures for mechanical and electrical equipment foundations. The data pool consisted of 263 activities; 180 were foundation concrete, and the other 83 were the other types of concrete activities.

RapidMiner (Mierswa & Klinkenberg 2018) was used as a tool for further processes. Rapidminer is a program that enables modifying the data and applying various Machine Learning techniques with a simple interface.

Raw data consists of planned quantities for each activity, weekly realized quantity for every data date, at completion quantity, project name, and project country for every activity. The data was manually transformed to distribute the attributes in the activity names to different columns for the machine-learning processes. In the early stages of the projects, planned quantity values were set to "1" for some of the foundation activities due to the unavailability of concrete quantity data during the baseline schedule development. As the concrete pouring activities progressed, these 'at completion' quantities for these specific activities were updated to reflect the actual volumes poured.

These activities need to be considered as outliers. The outlier is the data far from the average value of a statistics group. Outliers may affect the statistics and results substantially; therefore, they must be removed from the pool. Normalization is required to detect outliers in data pools with actual values, such as the one in this study, to ensure that variables with different scales are brought to a standard scale, preventing biased results.

In order to apply this process, the model in Fig. 1 was created.

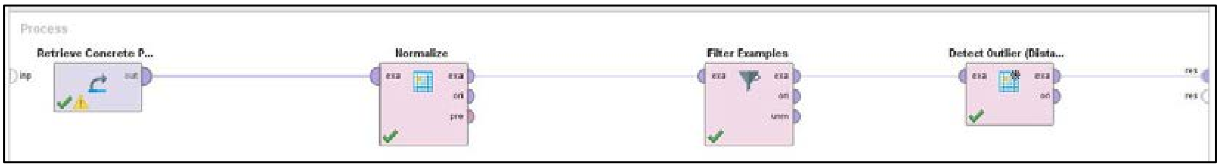

Fig.1: Outlier Detection Model

Due to the abundance of foundation concrete activities, the algorithm considered the "non-foundation" entries as outliers in a previous model. Thus, a "foundation concrete activities" filter was applied to detect outliers only among the foundation activities. The model detected five excessive values (which have value of 1 m^3 as Planned Quantity) as outliers, and these rows were deleted. After clearing the outlier entries, the new model in Fig.2 was created with clean data.

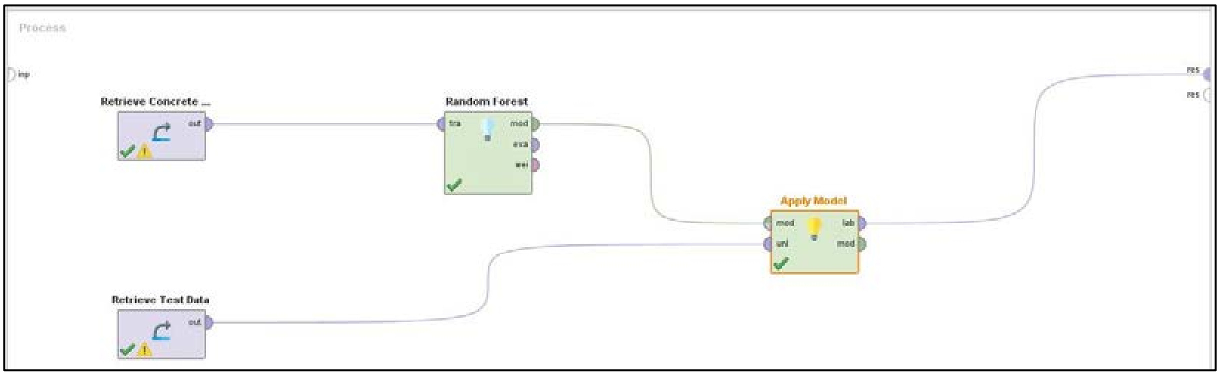

Fig.2: Random Forest ML Model

The input data consists of 5 different columns;

1- Activity ID: It is a unique ID for each activity.
2- Country: It includes the country project taking place.
3- Element Type: Element Type is the type of concrete element, which can be the foundation, column, slab, pedestal, wall, or trench.
4- Planned Quantity: It is the quantity planned at the beginning of the project, according to the baseline schedule.
5- At Completion Quantity: At Completion Quantity is the actual quantity on the site, which often differs from the planned quantity for various reasons.

Activity ID is unique for every row; the country column may include Iraq, Turkmenistan, or Uzbekistan. Element Type is the type of concrete element, which can be a foundation, slab, column, etc. Planned quantity is the quantity specified and planned at the beginning of the project, and At Completion, Quantity is the updated actual quantity throughout the project.

The model learns through the upper arm and applies the process to the Test Data (Table 2) below at the merging point (Apply model). Test Data consists of not started activities from the same three countries; thus, the table does not have at-completion quantities, leaving filling this column to the ML model.

Table 2: Structure of the Test Data

Activity ID	Country	Element Type	Planned Quantity
T_Act1	Iraq	Foundation	286.7
T_Act2	Iraq	Foundation	35.89
T_Act3	Iraq	Foundation	201.49
T_Act4	Turkmenistan	Foundation	31.25
T_Act5	Turkmenistan	Foundation	90.89
T_Act6	Turkmenistan	Foundation	219.19
T_Act7	Iraq	Slab	40.8
T_Act8	Turkmenistan	Slab	23.5
T_Act9	Uzbekistan	Slab	84.5
T_Act10	Iraq	Column	99.21
T_Act11	Turkmenistan	Column	137.69
T_Act12	Uzbekistan	Foundation	140.7
T_Act13	Uzbekistan	Column	175.55
T_Act14	Iraq	Pedestal	121.79
T_Act15	Turkmenistan	Pedestal	132.37
T_Act16	Uzbekistan	Pedestal	212.58
T_Act17	Uzbekistan	Column	90.05
T_Act18	Turkmenistan	Foundation	196.72
T_Act19	Iraq	Foundation	114.84
T_Act20	Turkmenistan	Foundation	108.51
T_Act21	Uzbekistan	Foundation	24.18
T_Act22	Turkmenistan	Wall	131.3
T_Act23	Uzbekistan	Wall	286.66
T_Act24	Turkmenistan	Pedestal	55.83
T_Act25	Uzbekistan	Pedestal	13.6
T_Act26	Iraq	Trench	272.11
T_Act27	Uzbekistan	Trench	155.09
T_Act28	Turkmenistan	Foundation	113.56
T_Act29	Turkmenistan	Foundation	91.76
T_Act30	Uzbekistan	Foundation	96.38

Random Forest regression was selected for the prediction process because more than two parameters affect the at-completion quantity: Country, Element Type, and Planned Quantity. Random Forest Regression is a widely used model in regression and classification problems. The accuracy of predictions increase when there are multiple decision trees.

3. RESULTS AND DISCUSSION

Although the amount is enough for consistency and prediction, usage of a broader data pool enables all the attributes to show effects on the results more clearly. For example, the projects' countries have many hidden variables affecting the quantities; however, this effect could not be seen clearly with only three countries. Also, most of the entries are for foundation concrete activities, so wall or column quantities did not affect the results as intended. Then, using the ML model with the input data in the test table, quantities of the activities were calculated at completion. The Final Table is given in Table.3 Forecasted "At Completion Quantities" are shown in the Prediction Column.

Table 3: Predictions on the Testing Data

Activity ID	Country	Element Type	Planned Quantity	Prediction
T_Act1	Iraq	Foundation	286.7	494.71
T_Act2	Iraq	Foundation	35.89	59.04
T_Act3	Iraq	Foundation	201.49	226.17
T_Act4	Turkmenistan	Foundation	31.25	34.41
T_Act5	Turkmenistan	Foundation	90.89	91.79
T_Act6	Turkmenistan	Foundation	219.19	269.12
T_Act7	Iraq	Slab	40.8	60.73
T_Act8	Turkmenistan	Slab	23.5	31.13
T_Act9	Uzbekistan	Slab	84.5	112.65
T_Act10	Iraq	Column	99.21	159.52
T_Act11	Turkmenistan	Column	137.69	130.16
T_Act12	Uzbekistan	Foundation	140.7	160.31
T_Act13	Uzbekistan	Column	175.55	208.09
T_Act14	Iraq	Pedestal	121.79	206.10
T_Act15	Turkmenistan	Pedestal	132.37	124.42
T_Act16	Uzbekistan	Pedestal	212.58	250.10
T_Act17	Uzbekistan	Column	90.05	122.94
T_Act18	Turkmenistan	Foundation	196.72	227.03
T_Act19	Iraq	Foundation	114.84	221.01
T_Act20	Turkmenistan	Foundation	108.51	66.39
T_Act21	Uzbekistan	Foundation	24.18	154.24
T_Act22	Turkmenistan	Wall	131.3	121.42
T_Act23	Uzbekistan	Wall	286.66	322.51
T_Act24	Turkmenistan	Pedestal	55.83	74.38
T_Act25	Uzbekistan	Pedestal	13.6	32.94
T_Act26	Iraq	Trench	272.11	422.71
T_Act27	Uzbekistan	Trench	155.09	208.74
T_Act28	Turkmenistan	Foundation	113.56	77.91

T_Act29	Turkmenistan	Foundation	91.76	91.79
T_Act30	Uzbekistan	Foundation	96.38	130.45

After inspecting the results and the graph in Fig.3, it was seen that they are consistent. Activities with Iraq in the Country column tend to differ the most from the baseline plan because projects in Iraq suffered from substantial design changes until their completion. On the other hand, the difference is lower in Turkmenistan activities because the baseline plan for the Turkmenistan project was closer to the realized work. Therefore, even if the graph has some more significant gaps, they are because of country and project differences. However, a more extensive data pool would enable predictions with less error if available. The rows with trench, pedestal, and walls do not have as much input data as foundation concrete activities; thus, these predictions may not be as accurate as foundation concrete activities. This study used country and element types as supplementary features to the planned quantities dataset. However, it is worth noting that including more comprehensive variables, such as detailed weather conditions, workforce experience, and material strength, which are known to impact quantities at project completion significantly, can further enhance the predictive accuracy of the model.

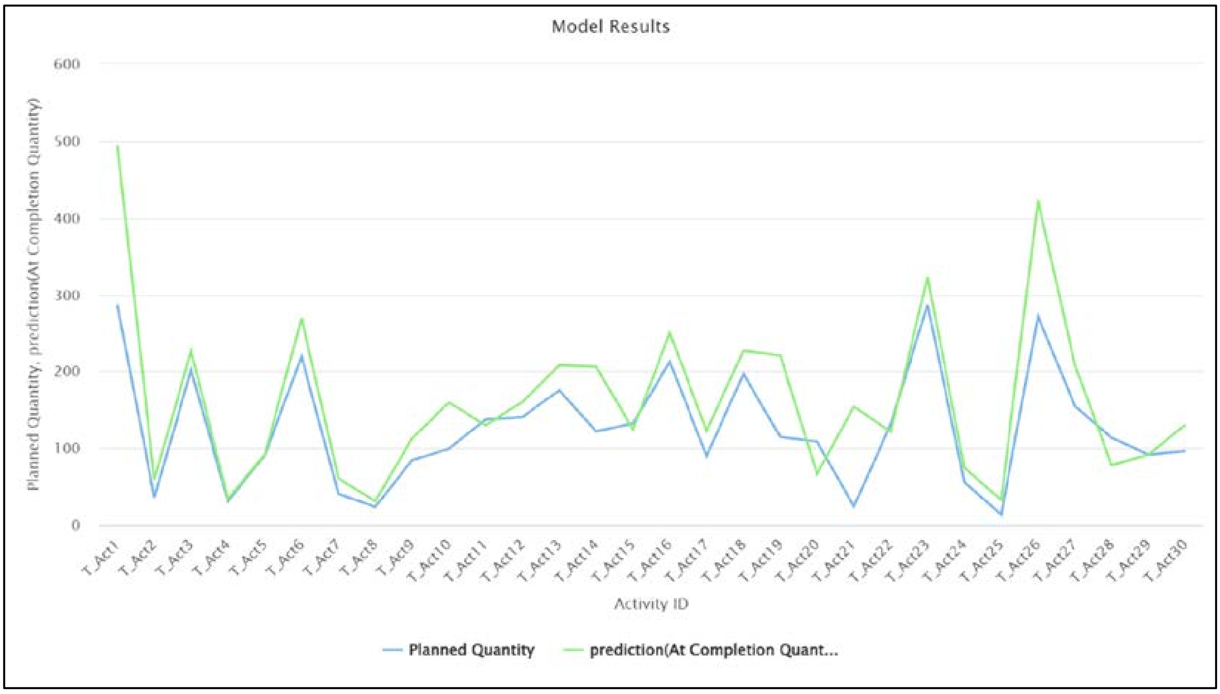

Fig.3: Graph of the Predictions

4. CONCLUSIONS

This study collected data from various ongoing and completed construction projects a construction company undertook, encompassing parameters related to concrete pouring activities. Utilizing advanced supervised learning algorithms, Machine Learning models were trained to establish correlations between planned and at-completion concrete quantities. While the model shows promising potential, it is important to note that future research could obtain more realistic and accurate results with more extensive and diverse data. The optimization of quantity forecasting is a key outcome, and the integration of Machine Learning-based forecasting offers powerful decision support for project management, enabling proactive measures to minimize delays and resource shortages. The successful implementation of Machine Learning underscores the importance of data analytics tools in the construction industry, which, with further exploration and expanded data availability, can lead to improved project management practices, resource utilization, and more profitable projects. It is essential for future research to address data limitations and consider real-time data integration to enhance the reliability and effectiveness of Machine Learning applications in the construction sector.

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CONCEPT FOR ENRICHING NISO-STS STANDARDS WITH MACHINE-READABLE REQUIREMENTS AND VALIDATION RULES

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ABSTRACT: *During building project planning, various standards, such as material specifications, value ranges, and construction regulations, must be considered. When analyzing a regulation for its BIM-based use, it must be identified which information can be checked directly or indirectly using a BIM model. The basis for the directly checkable information requirements is the explicit description of object classes, object types, properties, and values. Additionally, complex validation rules can be derived from the standards. These information extractions are mostly performed manually and laboriously on text-based regulatory documents. To provide a better data format, the NISO proposed the Standard Tag Suite (NISO-STS), which is an XML format for publishing and exchanging full-text content and metadata of standards. This paper proposes a concept to enrich standards in NISO-STS format with information requirements and validation rules to provide a machine-interpretable semantic knowledge base for BIM processes. To achieve this, the concept utilizes natural language processing (NLP) methods to extract semantic information from the standards. Furthermore, the paper introduces a workflow to transfer the gathered knowledge into the XML-based standard. This allows the acquired semantic knowledge to be used BIM-based and directly updated in future versions of the standards. To show the applicability of the concept an approach is presented in which the obtained information is stored and used as a queryable knowledge base. The resulting database is used by a querying assistant, in which a user can enter keywords and questions that are translated into SPARQL queries to provide answers for the given input.*

KEYWORDS: *Natural Language Processing (NLP), NISO-STS (Standard Tag Suite), Smart Standards, Rule-based model checking, Semantic knowledge*

1. INTRODUCTION

In civil engineering, managing and exchanging information is a non-trivial task due to the complex nature of construction projects and the involvement of numerous stakeholders (Alani et al., 2021; Tomczak et al., 2022). These stakeholders in the Architecture, Engineering, Construction, and Operations (AECO) industry put their priority on ensuring compliance with standards, regulatory documents, and other requirements (Beach et al., 2015). However, formalizing the Information Requirements (IR) and intricate validation rules poses a significant challenge and has hindered the widespread adoption of Building Information Modeling (BIM) practices (Tomczak et al., 2022). The current manual compliance checking process is prone to errors, time-consuming, and costly. Due to the high effort required for the testing processes, in practice testing is only carried out on a random sample and not in its entirety (Z. Zhang et al., 2022, Fauth, 2021). These drawbacks have motivated extensive research into Automated Compliance Checking (ACC).

Acquiring precise IRs and validation rules from guidelines and standards remains a significant obstacle, particularly considering that many of these documents exist in non-machine-readable formats (Schönfelder & König, 2021). Thus, there is a need for a machine-readable and interchangeable format of representation for regulatory documents and standards to extract the desired information for ACC checking. To tackle the challenge of not machine-readable standards, the German Institute for Standardization (DIN) has started the Initiative Smart Standards (Czarny et al., 2021). Their objective is to convert their published standards into machine-readable documents. To fulfill this, they have adopted the NISO Standard Tag Suite (NISO-STS), an XML-based extendable data format introduced by the National Information Standards Organization (NISO). This standardized format is designed to present and preserve the content and metadata of standards and regulatory documents (NISO Standards Tag Suite Working Group, 2017).

This paper presents a concept for enhancing standards and regulatory documents in the NISO-STS format with IR and validation rules. The aim is to establish a machine-interpretable semantic knowledge base that can be seamlessly integrated into BIM processes. To achieve this, natural language processing (NLP) methods are facilitated to extract relevant semantic information from standards in NISO-STS representation. Furthermore, the concept introduces a workflow to transfer the gathered knowledge back into the XML-based standard to link the extracted IRs and rules with the original text. This allows the extracted semantic knowledge to be used on a BIM basis and updated directly when new versions of the standard are created. To show the applicability within BIM

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Sven Zentgraf, Sherief Ali, Markus König, *Concept for Enriching NISO-STS Standards with Machine-Readable Requirements and Validation Rules,* pp. 718-728, DOI 10.36253/979-12-215-0289-3.72

workflows, the paper concludes with a demonstrator that can be used to query the semantic knowledge to obtain relevant validation rules and IRs. Overall, this paper aims to address the challenges faced in ACC, information management, and integrating digital information into the BIM workflow.

2. BACKGROUND

This section presents the key terms, concepts, and relevant research for the concept presented in this paper. Initially, the section provides an overview of the Standard Tag Suite developed by the NISO, followed by an introduction to the Initiative Smart Standards proposed by the DIN, which employs this tag suite. Following, an introduction to NLP-based information extraction and knowledge representation is provided. The chapter concludes with a presentation of the current state of research on the topic of code compliance.

2.1 Digital standards

As denoted in Section 1 there is a need for machine-readable, interchangeable, and maintainable regulatory documents and standards for ACC (Schönfelder & König, 2021). For this purpose the NISO in particular the NISO Standards Tag Suite Working Group published the NISO Standards Tag Suite (NISO-STS) in 2017 (NISO Standards Tag Suite Working Group, 2017). The NISO-STS defines a set of XML elements and attributes that describe the complete content and metadata of standards. This includes co-produced standards and standards bodies' adoptions of existing standards, to establish a universal format for publishing and exchanging standards content in all shapes. The primary objective of the NISO-STS is to preserve the content of standards, irrespective of how they were created and delivered. It enables the acquisition of structural and semantic components without being bound to a specific order or textual arrangement. The standard consists of two implementations, referred to as the Interchange Tag Set and the Extended Tag Set. These Tag Sets are constructed from the elements and attributes defined in the NISO-STS and are designed to function as models for publishing and enhanced interoperability of standards and regulatory Documents (NISO Standards Tag Suite Working Group, 2017).

Within Initiative SMART Standards (IDiS) of the DIN, the concepts and implementations of the NISO-STS are used to advance the digitalization of German regulations and standards (Czarny et al., 2021). The IDiS facilitates the establishment of digital standards, which offer information necessary for standardization tasks in a suitable format and scope. A whitepaper has been developed to foster a common understanding and clear action scenarios for implementing digital standards. The document provides a comprehensive understanding of various scenarios concerning standards, encompassing aspects such as maturity, readability, feasibility, interpretability, and even the potential for machine-driven creation. It also addresses the different levels of autonomy in the creation and application of standards and regulatory documents. These levels span from level 0, representing the traditional paper-based format, to a potential level 5, depicting a future scenario where standards are directly influenced and optimized by artificial intelligence (AI). Currently, the DIN is actively engaged in converting all its rules and regulations into a machine-readable XML serialization using the aforementioned NISO-STS model. To effectively implement rules for the ACC of building information models, digital standards at level 3 or higher are necessary. This indicates that the standards must reach a level of autonomy where they can be interpreted and applied by humans and machines (Czarny et al., 2021).

In this contribution, Autonomy Levels 2 and 4 are utilized. A document in Level 2 is a machine-readable XML document and allows the extraction of its textual content and other structural elements for further processing. Within the document's chapters, sentences, graphics, and tables are distinguishable which simplifies a separate examination of the individual components. A Level 4 document contains, in comparison to a Level 2 document, not only machine-readable but also machine-interpretable content that enables a close linkage with execution and application information. These features allow seamless integration of the contained information into other information systems and software tools (Czarny et al., 2021).

2.2 NLP-based information extraction

In the construction industry, the checking of specifications from building codes, regulations, and standards plays a crucial role. Stakeholders involved in a construction project must adhere to precise guidelines in both design and realization, and adherence to these guidelines needs to be consistently proven. One way to ensure compliance is through ACC of building designs. However, for ACC to work effectively, it requires converting the natural language specifications found in regulatory documents into machine-readable constraints (Fuchs & Amor, 2021). To achieve this, NLP methods can be facilitated. NLP is a subfield of AI and computer linguistics that focuses on the interaction between computer or formula languages and human language. It involves the development of algorithms and language models that enable machines to understand, interpret, generate, and manipulate human language effectively (Chowdhary, 2020). NLP utilizes a diverse set of techniques to gain a comprehensive understanding of natural language. These techniques have been applied in various studies to facilitate the full automation of the code compliance process during information extraction from regulatory documents.

Schönfelder and König (2021) proposed a Named Entity Recognition (NER) based model that trained German building code documents on the pre-trained German corpus BERT (Bidirectional Encoder Representations from Transformers). BERT is a language representation model, which is pre-trained on the deep-directional representation of unlabeled text. BERT has shown promising results in eleven natural language processing tasks such as question answering and language inference (Devlin et al., 2019). Schönfelder and König (2021) used the NER technique to label text in the building code as they aimed to train the network based on supervised learning. The study demonstrated results of average performance values of 95.7 % precision and 95.2 % recall. The authors discussed limitations in the study as the proposed concept could provide good results only to the German corpus used.

Some studies employ another technique besides NER as Zhou et al. (2022), and R. Zhang and El-Gohary (2020). Zhou et al. (2022) proposed an approach that deploys NER and Context-Free Grammar (CFG) to formulate a generalized rule interpretation framework. The study focused on analyzing regulatory text to create a syntax tree representing roles and concepts and developing a deep learning network using transfer learning to label the semantic elements in the text. Zhou et al. (2022) presented outcomes with an accuracy of 99.6 % and 91.0 % for parsing single- and multi-requirement sentences. The study stated that it focused on quantitative sentences in the regulatory documents and that more types of sentences will be addressed.

In their work, R. Zhang and El-Gohary(2020)introduced a new machine learning-based approach to automatically match building-code concepts and relations with their equivalent concepts and relations in the Industry Foundation Classes (IFC). The approach was implemented and tested on chapters from the 2009 International Building Code (IBC) and the Champaign 2015 IBC Amendments. The preliminary results achieved a semantic matching performance of 77 % accuracy for matching building-code concepts to IFC elements and 78 % accuracy for matching building-code relations to IFC relations.

2.3 Knowledge representation

There are two fundamental concepts for data and knowledge representation, which are ontologies and knowledge graphs. Ontologies are used widely in various domains to represent the semantics of a specific domain and provide standardized data representation (Ehrlinger & Wöß, 2016). The Interconnected Data Dictionary Ontology (IDDO), developed by Zentgraf et al. (2022), was designed to digitize knowledge from building regulations and construction guidelines. It offers a data schema to describe and manage properties in accordance with ISO 23386 (ISO 23386, 2020). The ontology organizes the digitized knowledge into a hierarchically structured tree of property groups and properties, extracted from natural language texts. Its main purpose is to provide an architecture for transforming building codes into a structured, knowledge-represented format. Encoded in Web Ontology Language (OWL) (Motik et al., 2012), it enables seamless integration and utilization of digitized knowledge in various applications.

Other studies focus on rule formulation from regulatory documents that help the development of ACC frameworks. Wessel et al. (2013) proposed an approach with two parts. The first part involves building an ontology to capture and represent the standards and information found in regulatory documents. In the second part, the enriched ontology is utilized to extract rules. These rules are derived from the information contained within the ontology, facilitating the automated extraction and formalization of regulatory guidelines and requirements. The author states that there are further improvements they are targeting in the future, which aim to enrich the knowledge base and improve automatic reasoning and extraction of rules (Wessel et al., 2013).

2.4 Code Compliance

Building codes are a part of the construction work, which aims to ensure the integrity and compliance of the planned structure. As the review of building codes is a time-consuming and error-prone process, there are a lot of efforts to digitize the process. Accordingly, many research studies use different methodologies to reach the goal of rule extraction. Eastman et al. (2009) stated that the process of rule checking is composed of four steps, which are (1) rule interpretation and logic structuring ; (2) building model preparation; (3) rule checking, and (4) reporting the checking results.

Schwabe et al. (2019) proposed an approach that aims to create a model-based rule checking for the planning of construction site layouts. The study used the open-source rule engine Drools and Industry Foundation Classes (IFC) to extract information from building models and apply rules to the information extracted. Drools is a Business Roles Management System (BRMS) based on Java language, which allows users to create decision models that are based on rules formulated as *when-then* statements, to take an action when a condition is true (Browne, 2009). Schwabe et al. (2019) stated that they are planning to extend the rule sets and experiments with other rule languages in future research.

In their work, Beach et al. (2015)introduced a method that utilizes the semantic web to achieve a comprehensive understanding of regulatory documents. The authors divided the semantic web knowledge into three main concepts, where each concept targets a specific knowledge in the regulation document. Additionally, the authors have used RASE tags to annotate the regulatory document, which is a markup technique applied to text and it is composed of four operators; Requirement, Applicability, Selection, and Exceptions (Hjelseth & Nisbet, 2011). Accordingly, Beach et al. (2015) converted the tags into Semantic Web Rule Language (SWRL), which can conceivably detect if the regulation is in the scope or not.

3. CONCEPT

This paper proposes a concept for the enrichment of digital standards in Level 2 with machine-readable IRs and validation rules to create digital standards at autonomy Level 4. The objective is to establish a machine-interpretable semantic knowledge base that can be integrated into the BIM methodology to support planning processes, ACC, and other BIM practices. To achieve this, an XML-Crawler first processes a digital standard at autonomy Level 2 to extract all contained textual information. This textual information is then forwarded into an NLP pipeline that extracts all relevant IRs and validation rules from the natural language texts. After the extraction the requirements and rules are further processed into suitable data representations and stored in respective databases. The stored data is then used to enrich the analyzed standard to make it compliant with autonomy Level 4 and additional areas of application for the stored data. Additionally, the entire concept is designed to be realized using open data formats and interfaces, aligning with the principles of the openBIM concept.

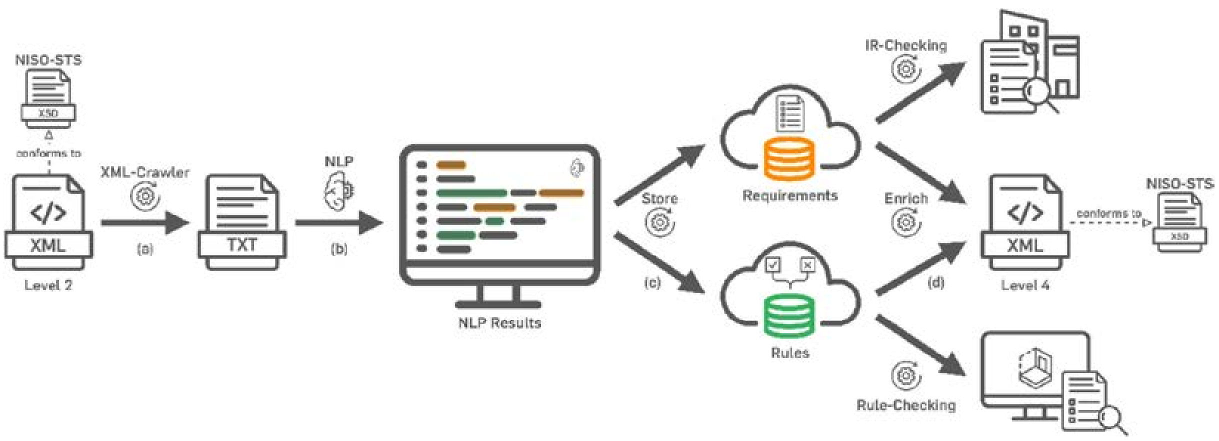

Fig. 1: Schematic representation of the concept

The input for this framework is as mentioned above an XML-serialized digital standard at autonomy Level 2. It complies with the XML Schema Definitions (XSD) specified by the NISO-STS. At Level 2, the document is machine-readable, enabling automated extraction of its structural elements. Granular contents such as chapters, sentences, graphics, and tables can be distinguished and extracted from the document (cf. Section 2.1). Moreover, the separation between representation and content allows a more streamlined and efficient processing of the information (Czarny et al., 2021).

In the initial step of the developed workflow, the uniform structure provided by the autonomy level is utilized. The structure allows the creation of an XML crawler that can efficiently extract all relevant textual information from the standard. A document or in this case, XML crawler is a software or script designed to automatically search and navigate through documents to extract information from these documents and store it for further processing, analysis, or database indexing. Document and XML crawlers are commonly used in search engines and knowledge management systems. The extracted textual data taken from the NISO-STS compliant standard is stored in a plain text format for further processing (cf. Fig. 1 (a)).

Subsequently, algorithms from the field of NLP can be trained using these text-based input data. The aim of the conceptualization, implementation, and training of NLP algorithms within the proposed concept is to find two or optimally one NLP pipeline to find and extract IRs and validation rules which can be further processed (cf. Fig. 1 (b)). To enable the training of such NLP pipelines, further preprocessing of the provided textual information may be necessary. This preprocessing could involve tasks such as sentence tokenization, lemmatization to revert words to their base forms, or conversion of input texts into vectorized representations.

In the third step, the output generated by the NLP pipeline, which includes the identified IRs and validation rules, is further processed (cf. Fig. 1 (c)). The goal is to find suitable data representations for both the IRs and the validation rules. This step involves transforming the extracted information into structured and machine-interpretable formats, making it more accessible for downstream tasks. To achieve this, databases are created to store and manage the extracted IRs and validation rules. These databases are designed to support the creation, storage, organization, exchange, and utilization of data in structured and machine-readable formats. Special attention is given to utilizing open interfaces to ensure interoperability and flexibility. By leveraging open REST (Representational State Transfer) APIs, the databases make the stored information available for seamless integration with other systems and applications.

The last step of the concept is divided into two parts. In the enrichment, IRs and validation rules stored are accessed through REST APIs. Leveraging this extracted data, the analyzed standard of Level 2 is enriched with the extracted elements to a smart standard in autonomy Level 4. As denoted in section 2.1 a Level 4 standard encompasses machine-interpretable content, strongly linked with execution and application information. This capability enables direct executability and seamless integration with other relevant information sources (Czarny et al., 2021). By incorporating machine-readable features, the standard becomes easily interpretable and executable by machines, minimizing the need for manual intervention. This automation enhances efficiency and precision in processes reliant on the standard. Furthermore, the integration of execution and application information allows the automation of specified actions and enables interactions between interconnected systems and data sources. With this enriched autonomy, the standard gains agility in handling dynamic tasks and adapting to changing scenarios. ACC and other complex procedures can be executed with greater effectiveness and consistency, supporting workflows, and enhancing data interoperability.

The second part of the final step focuses on other areas of application of the information extracted from the standards. Fig. 1 (d) illustrates an exemplary area of application of the automatic validation of IRs and validation rules directly at a BIM model, both formally and technically. This type of validation could be integrated into the lifecycle of a construction project during a digital building permit review process. There are several other potential applications for the provided information. For instance, it could be utilized to define the Level of Information Need (LOIN) during the tendering process of buildings or to formulate general modeling guidelines for construction projects. Moreover, it can also support the creation and versioning of new or existing standards, facilitating a more streamlined and efficient standardization process.

By offering different possibilities for leveraging the extracted information requirements and validation rules, this shows the relevance and impact of the NLP-based analysis of standards and regulatory documents in the AECO domains. It enables stakeholders in the construction industry to implement automated validation processes, more streamlined tendering procedures, and maintain consistent modeling practices, leading to improved efficiency and enhanced collaboration throughout the entire construction lifecycle.

4. USE CASE

We aim to develop an approach to convert the knowledge in regulatory documents into a machine-interpretable representation. As the regulatory documents are mostly not computer processable, the purpose is to represent the knowledge in the regulatory document in a knowledge base, which is computer interpretable. Accordingly, the next step is that we apply the rules based on the retrieved data as illustrated in Fig. 1 on a regulatory document.

The regulatory documents used in this demonstrator are from the Research Society for Roads and Traffic (FGSV) (FGSV Verlag GmbH, 2023), which creates the technical regulations for the entire road and traffic system in Germany. The regulation’s language is German, but the concept has broad applicability and can be extended to any other language. The FGSV has multiple regulations in this area, while we focused on FGSV 499 – RStO12

(Forschungsgesellschaft für Straßen- und Verkehrswesen, 2012). The proposed use case places particular emphasis on one chapter of the mentioned regulatory document. The chapter encompasses introductory text, definitions, tables, and interrelated constraints. The approach of knowledge extraction required extensive and comprehensive reading and understanding of the document, to extract the correlations and interrelationships in the text. The knowledge acquisition is performed manually by highlighting the logical sentences, descriptive texts, and the relationships between the tabulated data and the plain texts.

4.1 Data Preparation

The subsequent action entails gathering the knowledge extracted in a machine-readable format, to be able to formulate rules upon the acquired information. The representation of knowledge is based on the semantic web by employing the OWL and the Resource Description Framework (RDF). The ontology hierarchy and relationships between classes is a complex stage that requires a significant amount of attention to achieve the accurate formulation of knowledge extracted. The software used to create the ontology is Protegé (Musen, 2015). The acquired knowledge from the regulatory document is centered around the construction of roadways. The regulatory document encompasses different classes of soils and the requirements for the subsoil or substructure according to frost sensitivity or other constraints. The soil classes have a minimum thickness delegated to each class and this thickness could be increased or decreased whenever exposed to local conditions, for instance depending on the zone, underground water conditions, or drainage of the roadway. Each local condition possesses a value, which has a positive or negative sign, to raise or lower the thickness of the soil class.

Table 1: Increased or reduced thicknesses due to local conditions (translated (Forschungsgesellschaft für Straßen- und Verkehrswesen, 2012))

Local conditions		**A**	**B**	**C**	**D**	**E**
Frost effect	Zone I	±0 cm				
	Zone II	+5 cm				
	Zone III	+15 cm				
small-scale Climate differences	unfavorable climatic influences, e.g., due to North-facing slopes or in ridge locations of mountains		+5 cm			
	no special climatic influences		±0 cm			
	favorable climatic influences with closed lateral development along the street		-5 cm			
Water conditions in the subsoil	No groundwater and stratum water down to a depth of 1.5 m below the subgrade level			±0 cm		
	Groundwater or stratum water permanently or temporarily higher than 1.5 m below ground level			+5 cm		
Location of the gradient	Incision, gating				+5 cm	
	Terrain height up to 2.0 m				±0 cm	
	Dam > 2.0 m				-5 cm	
Drainage of the roadway/execution of the edge width	Drainage of the roadway via swales, ditches, or the embankments					±0 cm
	Drainage of the roadway and peripheral areas via gutters or drains and pipelines					-5 cm

Furthermore, the regulatory document comprises a section on asphalt base courses, where tabulated data shows different types of base layers without binders and each type has a thickness depending on the load-bearing capacity (cf. Table 1).The document encompasses abundant data about how to construct the roadways and the constraints encountered, which affect the substructure or superstructure. The stated knowledge is represented as an ontology through different classes and properties. To ensure the ontology's coherence and compatibility, it is structured based on the IDDO (Zentgraf et al., 2022), which provides an architecture for transferring building codes into a structured format based on the data schema of ISO 23386 (ISO 23386, 2020). As a result, the knowledge is well structured through classes and properties in a standardized way.

4.2 Information retrieval

As a prerequisite, it is assumed that the conversion of the regulatory document into a machine-readable format was achieved successfully. The prevailing stage is to retrieve the information stored in the knowledge base in order to be able to apply rules to the retrieved data. The chosen retrieval method is the SPARQL Protocol and RDF Query Language. SPARQL is selected due to its ease of use and applicability to manipulate RDF data, which supports the proposed framework. The ontology is established and structured using Protegé. To enhance the concept's capabilities and prepare for the subsequent step of formulating rules, the queries are interconnected with the RDF data. The querying stage starts with trials to ensure the functionality of the ontology, whether the data is retrieved correctly or not. The objective is to retrieve the classes, properties, and annotations from the ontology. We used to identify the vocabulary from the ontology precisely as SPARQL queries are sensitive and comply with the class naming pattern in the ontology. As a case in point, to begin with, we utilized the first part of the regulatory document, which aims to find the minimum thickness for soil classes. The soil classes are *F1*, *F2*, and *F3*, where each one has a relationship to a local condition. The main class in the ontology, which stores the soil classes is named *Frostempfindlichkeitsklasse*, thus we call the main class in the queries, to get the subclasses, annotations, and relationships assigned to it. The objective is to retrieve the thickness of the soil class, as well as the thickness assigned to the local condition. As a result, the total thickness of the soil class could be calculated, and the final thickness is the sum of the soil thickness and the local condition thickness variable. The final thickness calculation will not be executed through SPARQL queries. This step will be calculated during the formulation of the validation rule instead.

```
WHERE
{{
        ?frostklasse rdfs:subClassOf ont:{class_name} .
        ?klasse rdf:type/rdfs:subClassOf* ?frostklasse .
        ?klasse ont:hasThickness ?Dicke .
        ?klasse ont:BoundaryValue ?Constraint .
        ?Constraint ont:hasThickness ?ConstraintDicke .
        ?GroupOfProperties ont:DateOfCreation ?DateOfCreation .
        FILTER (regex(str(?klasse), "{klass}", "i") && regex(str(?Constraint), "{condition}", "i"))
 }}
GROUP BY ?frostklasse ?Dicke ?klasse ?Constraint ?ConstraintDicke ?DateOfCreation
```

Fig. 2: Excerpt of an example query for detecting the Soil class, the Thickness, the Local condition, and the Local condition

As an example, Fig. 2 shows an excerpt of a query formulated for Rule 2, which detects the Frostklasse (Soil class), Dicke (Thickness), Constraint (Local condition), and Constraint Dicke (Local condition thickness). The same pattern of query formulation is employed for other knowledge data stored in the ontology, taking into account the distinctions in parameters.

4.3 Rule Checking

Our purpose is to build a framework that consists of three components, which are ontology, SPARQL queries, and the Python programming language for conducting additional analysis on the retrieved data and rule development. The rule's structure consists of a condition part *if statement* and the outcome part *Then and Else statements*. Thus, the rules are formulated to execute the results based on specific conditions.

For instance, a rule logic is *if the user selects a class named X*, and *if the user selects a local condition named Y,* then the data for the assigned class based on the local condition selected by the user will be retrieved. Accordingly, some actions will be executed and applied to the retrieved data. For example, the aim is to calculate the final thickness of the subgrade, where the thickness depends on the minimum thickness. This is specified depending on the soil class and local conditions, to increase or decrease the total thickness of the substructure. As a result, the rules calculate the final thickness of the substructure based on the class selected by the user and the local condition selected as well. One of the significant aspects taken into account is that not all the data can be retrieved from the knowledge base with only one SPARQL query, thus every rule formulated has its query. Three rules have been derived from the knowledge extracted from the regulation document.

4.4 User Interface

In the upcoming step, a user interface is implemented, which uses the created validation rules and the converted excerpt from the regulatory document. The aim is to allow the user to interact with the regulatory document through input provision and rule selection. We developed a user interface, which prompts the user for input, such as keywords, filters, or specific entities directly into the interface. Accordingly, the system uses the input to construct a SPARQL query to retrieve the relevant data in the ontology. Furthermore, the interface provides users with a list of pre-defined descriptive rules, each designed to process data based on a certain logic. Additionally, once the user selects a rule, the interface provides an instruction statement, which guides the user on what the system needs to process the data as illustrated in Fig. 3.

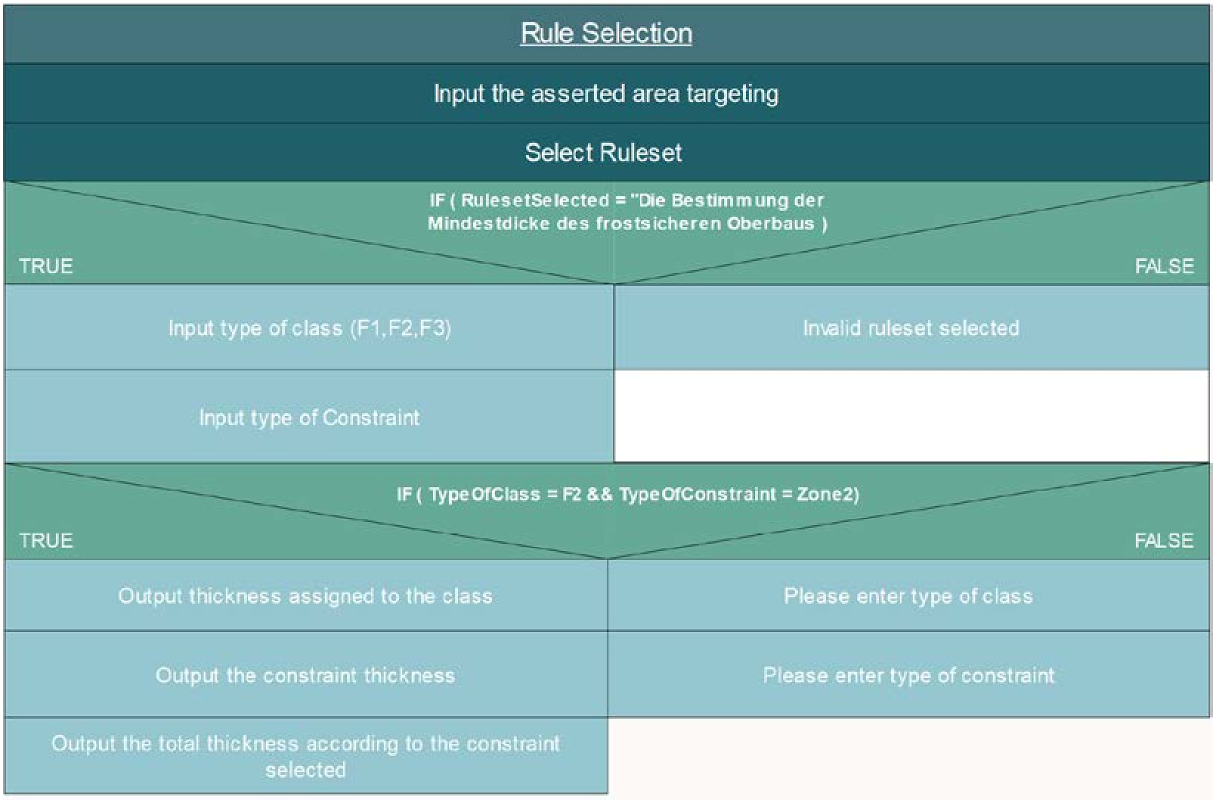

Fig. 3: Nassi-Schneidermann diagram of the program logic of the user interface

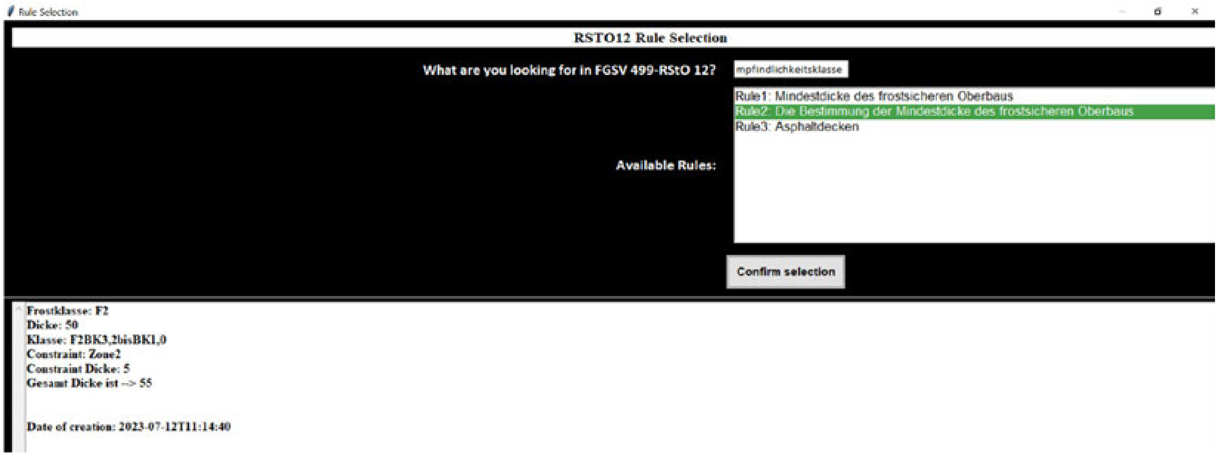

Fig. 4: Results based on the class name specified and the selected rule

The integration of SPARQL and Python rules delivers a comprehensive solution to interact with the knowledge base and perform rule-checking. This process enables the users to interact with the ontology. Fig. 4 shows the prototype of the implemented user interface.

5. CONCLUSION

This contribution provides a concept to enhance digital standards in Level 2 by incorporating machine-readable IRs and validation rules to advance these digital standards into autonomy Level 4. The concept uses an XML document crawler and NLP algorithms to analyze the textual information of an examined standard. The extracted IRs and validation rules are converted and stored in semantic knowledgebases and are made available via open RESTful APIs. With these open interfaces, the rules and requirements can be used to transform the considered standard into a machine-interpretable standard of autonomy Level 4. Furthermore, the gathered rules and requirements can be used in other areas of application within the BIM methodology (cf. Section 3).

One of these application areas is presented in detail in the use case (cf. Section 4). An approach is presented in which the obtained information can be used as a queryable knowledge base. For this purpose, it is assumed that a standard was processed by the NLP algorithm in advance and that the results are available for further processing. In the next step, the obtained information is structured according to the IDDO ontology and stored in a graph database. The resulting database is used as a semantic knowledge base for a querying assistant in the following. Within the assistant, the user can input a fixed set of inputs to query the knowledge base. The entered keywords and questions are translated into SPARQL queries which search the knowledge base to provide the user with an answer to the given input. The presented use case shows the feasibility of the presented concept with a restricted set of possible filters and questions. In future research, it can be considered to extend pre-trained networks, like ChatGPT, by incorporating extracted information from standards and regulatory documents.

Current parts of the concept have already been implemented while others need to be addressed in future work. In their work, Kandt and Zentgraf (2023) presented the implementation of an XML-Crawler for NISO-STS-compliant standards. With the outcome of this contribution, the process step shown in Fig. 1 (a) can be realized. The aforementioned IDDO ontology published by (Zentgraf et al., 2022) can be used to create a graph database for information requirements (cf. Fig. 1 (c)). Apart from outlining the data schema, the paper also introduces a method demonstrating how IDDO can ensure the accuracy of information requirements through the application of Shapes Constraint Language (SHACL) shapes.

In future research, several areas need to be addressed to realize the whole of the presented concept. Firstly, the identification of suitable NLP algorithms for extracting information requirements and validation rules is important. In the following step, it is necessary to define and establish a dedicated database to store, manage, and maintain the extracted validation rules. Building upon this, methods must be developed to automate the enrichment of a Level 2 standard using the extracted information requirements and validation rules, in order to obtain a Level 4 standard. Additionally, potential application areas within the building lifecycle need to be explored. Possible areas where the extracted information could be utilized effectively include Facility Management, refurbishments in combination with sustainability assessments, and other areas.

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TRANSFORMING BUILDING INDUSTRY KNOWLEDGE MANAGEMENT: A STUDY ON THE ROLE OF LARGE LANGUAGE MODELS IN FIRE SAFETY PLANNING

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ABSTRACT: *This paper discusses the potential use of AI in general, and large language models (LLMs) in particular, to support knowledge management (KM) in the building industry. The application of conventional methods and tools for KM in the building industry is currently limited due to the large variability of buildings, and the industry's fragmentation. Instead, relatively labor-intensive methods need to be employed to curate the knowledge gained in previous projects and make it accessible for use in future projects. The recent development of LLMs has the potential to develop new approaches to KM in the building industry. These may include querying a variety of relatively unstructured documents from previous projects and other textual sources of technical expertise, processing these data to create knowledge, identifying patterns, and storing knowledge for future use. A proposed framework is defined for the use of LLMs for KM in construction. We will perform preliminary analyses on how to train models that can generate information and knowledge required to make decisions in the development of specific tasks of fire safety planning.*

KEYWORDS: *Large Language Models (LLMs), Knowledge Management (KM), Fire Safety Planning, Expert Systems (ESs), Artificial Intelligence (AI), Knowledge Graph, Ontology.*

1. INTRODUCTION

In the building industry, ensuring fire safety is of paramount importance. Effective fire safety planning plays a crucial role in mitigating risks, protecting occupants, and minimizing property damage (Kodur et al., 2019). However, the complex and dynamic nature of the building industry poses unique challenges in the realm of fire safety planning such as high fuel (fire) load, improper use of the materials, use of new construction materials with poor fire performance or longer response times for firefighting (Kodur et al., 2019; Parsamehr et al., 2023). Conventional methods and tools for knowledge management (KM) have struggled to adequately address these challenges due to the industry's inherent variability and fragmentation (Nikolic & Dakic, 2015).

Traditionally, fire safety planning has been based on expert knowledge (Maiellaro, 1997; Law & Spinardi, 2021). To curate and leverage the knowledge gained from previous projects for future endeavors, the building industry has relied on labor-intensive approaches. These approaches involve manually extracting and organizing information from disparate sources, making it time-consuming and resource-intensive (Liu, 1995). Consequently, the development and implementation of efficient fire safety planning strategies are hindered, hampering the industry's overall progress.

Expert systems (ESs) have been developed to capture and codify this expert knowledge, making it more accessible to fire safety professionals. However, ESs have a number of limitations, including the fact that they are difficult to maintain and update, and they can be inflexible in dealing with new or unforeseen situations (Tofiło et al., 2013).

Nevertheless, recent advancements in the field of Artificial Intelligence (AI), particularly in large language models (LLMs), offer new opportunities for overcoming knowledge management issues in the building industry. LLMs are a type of artificial intelligence (AI) that are trained on massive datasets of text and code (Shanahan, 2023). This allows them to learn the relationships between concepts and to generate text that is both informative and comprehensive. LLMs, such as OpenAI's GPT-3.5, have the potential to revolutionize the way knowledge is accessed, processed, and utilized.

The utilization of LLMs in fire safety planning offers the potential benefits of accessing and processing extensive data from previous projects, identifying patterns and trends in fire safety data, generating novel knowledge and insights, and adapting to new or unforeseen situations. These advancements can significantly improve decision-making processes and enhance the overall effectiveness of fire safety planning in the building industry.

Therefore, the primary goal of this paper is to investigate and assess the potential of LLMs in the context of fire safety planning. In pursuit of this objective, the current state of the art in expert systems (ESs) employed for fire

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)

Ori Ashkenazi, Shabtai Isaac, Alberto Giretti, Alessandro Carbonari, Dilan Durmus, *Transforming Building Industry Knowledge Management: A Study on the Role of Large Language Models in Fire Safety Planning,* pp. 729-738, DOI 10.36253/979-12-215-0289-3.73

safety planning will be conducted and LLMs will be introduced as an innovative approach to help define scenarios to ESs. Finally, the research will demonstrate the preliminary test results and conclude with future research directions in order to realize the full potential of LLMs for fire safety planning.

2. THE CHARACTERISTICS OF ESS AND LARGE LANGUAGE MODELS (LLMS)

AI systems process and analyze large datasets with the view of identifying patterns, relationships, drawing inferences, recommendations and taking action. With the advancement in AI, conversational AI came of age in 2010 to deal with the application of Natural Language Processing (NLP) to enable computers to interact with humans in a conversational way using natural language. The majority of the developed conversational AI agents in the AEC industry are based on the traditional approach to NLP, which requires time for processing the data, and users' interactions are often restricted as the agents are developed with the assumption of happy path users (Saka A. et al., 2023). Large Language Models (LLMs) are neural networks with large parameters and are trained using self-supervised learning and semi-supervised learning on large datasets. LLMs have improved NLP and shifted the direction away from training with labeled data for defined objectives. Generative Pre-trained Transformer (GPT) models which are decoder blocks only from OpenAI have gained significant attention and showed improved performance from GPT-2 (trained with 10 billion tokens) until the latest GPT-4 released in 2023. GPT models use transformer-based models that learn statistical patterns of natural language, enabling them to generate human-like language. One of the main advantages of GPT models is their capacity to produce language that is cohesive, fluent, and nearly indistinguishable from any text produced by humans. These models have been effectively used in a variety of applications, including chatbots, content generation, and machine translation. They can produce answers to open-ended questions, making them an important tool for natural language communication.

Not only have the communication and inference abilities demonstrated to emerge naturally in large language models, but even dedicated experiments have shown that chain-of-thought (COT) prompting improves performance on a range of arithmetic, commonsense, and symbolic reasoning tasks. Indeed, one's own thought process when solving a complicated reasoning task such as a multi-step math word problem entails decomposing that problem into intermediate steps and solving each of them before giving the final answer. A research endowed language models with the ability to generate a chain of thought, i.e. a coherent series of intermediate reasoning steps that lead to the final answer for a problem. It was reported that sufficiently large language models can generate chains of thought if demonstrations of chain-of-thought reasoning are provided in the examples for few-shot prompting (Wei J. et al., 2022). The motivations that led to the development of the chain-of-thought prompting method match the main goals that must be pursued in the field of knowledge management in construction. First, the chain of thought, in principle, allows models to decompose multi-step problems into intermediate steps, which means that additional computation can be allocated to problems that require more reasoning steps. Second, a chain of thought provides an interpretable window into the behavior of the model, suggesting how it might have arrived at a particular answer and providing opportunities to debug where the reasoning path went wrong. Third, chain-of-thought reasoning can be used for tasks such as math word problems, commonsense reasoning, and symbolic manipulation, and is potentially applicable (at least in principle) to any task that humans can solve via language. Finally, chain-of-thought reasoning can be readily elicited in sufficiently large off-the-shelf language models simply by including examples of chain-of-thought sequences into the examples of few-shot prompting (Wei J. et al., 2022). Among the main findings from this study, we would like to stress that chain-of-thought prompting does not positively impact performance for small models, rather it has larger performance gains for more-complicated problems. In addition, chain-of-thought prompting via GPT-3 compares favorably to prior state of the art, which typically finetunes a task-specific model on a labeled training dataset.

Although the construction industry is information-intensive and relies on myriad and diverse information from different stakeholders, there is a lack of information integration, reuse, and efficient management, all of which have an impact on the productivity of the industry. In other words, we must find out how to represent large amounts of diverse knowledge in a fashion that permits their effective use and interaction (Goldstein I, & Papert S., 1977). An expert system is a computer program whose performance is guided by specific, expert knowledge in solving problems. The problem-solving focus is crucial in this characterization because there must be the knowledge of central interest that can guide the search for solutions. The word "expert" implies narrow specialization (or focus) and substantial competence. It is intended to solve problems that are otherwise solved by people having dedicated training and exceptional skills. Thus, the standard of performance for expert systems is in human terms, by comparison with people carrying out a particular kind of task (Stefik M., 2014). Nowadays, expert systems are being used in a wide range of different interactive roles, such as smart spreadsheets, financial advisors, planning assistants, and cognitive coprocessors. In whatever role we employ expert systems, those systems require knowledge to be competent, the so-called knowledge base. Such knowledge must be elicited through effective techniques from multiple human experts. Then, techniques to process such knowledge should be adopted to work out a robust, reliable, and flexible expert system (Fekri-Ershad, S., 2013). Even in the most successful applications where expert systems outperform human experts in their reliability and consistency of results, expert systems have less breadth and flexibility than human experts. In this context, LLMs can help enhance the flexibility and reliability of expert systems, thanks to their ability to manage large amounts of information, even if it is not structured such as written documents, technical standards and regulations. GPT models are trained using vast amounts of unstructured text data, enabling them to generate language almost indistinguishable from human-generated text (OpenAI, 2023). The synoptic chart included below as Table 1, discusses how LLMs can be a potential tool for improving knowledge management in the building industry. LLMs can help widen the scope of expert systems thanks to their ability to scrape information from any (even) unstructured knowledge sources as soon as it is made available. Hence, they can increase and update the knowledge base of an expert system and set up decisional processes that integrate advanced paradigms.

Table 1: Leveraging LLMs to enhance decision-making in combination with expert systems

	Expert Systems	***Large Language Models***
Goal	*Supporting decision-making with a specific task*	*Eliciting additional information to broaden out the expert system*
Input	*Quantitative and structured data*	*Any type of (even) unstructured data*
Approach	*Combination of logical rules and a knowledge base to make inferences*	*Deriving statistical patterns from evidence and performing reinforcement learning*
Method	*Symbolic AI*	*Transformers*
Interface	*Digital*	*Answers to questions in human-like language / chain-of-thought*
Output	*Recommendations and advice for specific scenarios*	*Arguing scenarios representing the dynamics of complex systems*

3. DISCUSSION OF GAPS AND COMPLEMENTARY ASPECTS

Few research works have applied GPT models in construction case studies. They mainly are concerned with information retrieval from BIM models and scheduling and sequencing tasks. These investigations helped find out inherent limitations, and they paved the way to an extended research review, that investigated opportunities and challenges about the practicality of GPT models in the construction industry (Saka A., 2023). These opportunities are categorized into different phases of the construction project lifecycle: predesign, design, construction, operation, and demolition.

In the pre-design phase, GPT models incorporated into predesign processes can help simplify decision-making, enhance communication among stakeholders, and speed up the discovery of design restrictions and possibilities. Similarly, they may support decisions with their powerful natural language processing and machine learning capabilities of evaluating data, delivering insightful suggestions, and promoting more efficient cooperation among stakeholders through real-time information and predictive analysis.

In the design phase, GPT models can automate regulatory compliance checks, reducing errors, and streamlining the design process. Other representative applications could be quantity take-off and costing (because GPT models can be leveraged by providing textual data for the model with necessary cost databases and estimation methods). If provided with information on standards, regulations, passive design principles, and renewable energy systems, GPT models can be leveraged for improving energy efficiency analysis.

In the construction phase, GPT models can capture and interpret textual information, enabling a more comprehensive understanding of construction project scheduling and logistics by means of a more flexible and intuitive approach than mathematical modeling. Other applications include dynamic risk identification and assessment by scrutinizing large volumes of project documents and historical data; enhancing progress monitoring and reporting by analyzing textual project updates and reports; site safety management; resource allocation and optimization; planning and organizing inspection and testing activities; claim and dispute resolution.

In the operation and maintenance phase, GPT can assist in predicting energy demand patterns, allowing for better planning and allocation of energy resources and providing customized recommendations. They could predict an asset's remaining useful life, predicting maintenance and repairs. They can be trained with relevant compliance documents, guidelines, and reporting requirements to capture patterns and embedded knowledge. These models can be used in compliance evaluation of facility management activities. Other applications might be space allocation for the best usage in a facility; generating sustainability reports; analyzing waste-related data.

In the demolition phase, GPT models can process large volumes of data, in order to: determine optimal demolition sequences, and recommend appropriate safety measures; optimize waste sorting and identify recyclable materials; offer the prospect of redeveloping and repurposing the site; analyze various risk factors and provide more accurate and objective assessments by leveraging their advanced natural language processing (NLP) and machine learning (ML) capabilities.

The analysis performed above suggests that some shared challenges must be faced:

1. Models are prone to hallucination, i.e. they give sound and plausible information that is not true, which reduces system performance and users' expectations.
2. Mainly structured data are usually needed in the fine-tuning of GPT models which are often not readily available in the construction industry; besides, availability and quality of data have been a major challenge for the application of artificial intelligence in the industry.
3. Although GPT models are large language models and trained on large data sets, their ability to understand domain-specific knowledge is limited. As such, there is a need for adequate fine-tuning of GPT models and the provision of context to improve their performance in a technical domain like the construction industry. Similarly, the regulations in the construction industry are many and vary over time.
4. GPT models are trained on large datasets. In the construction industry, data such as project design, cost, contracts, and schedules could be used as inputs, raising the concern of confidentiality of GPT models generating output with sensitive information.
5. There is often resistance to change in the industry. With the growing application of AI, industry practitioners and stakeholders are skeptical about trusting and accepting it.
6. Liability and accountability challenges are due to the training on a large amount of data. Bias, incomplete information and inaccuracies in the training data would affect the output generated by the models.
7. Deployment of GPT models in the construction industry requires new skill sets called "prompt engineering" and training programs for professionals. There are several techniques available for prompt engineering such as zero-shot (i.e. no examples are provided for the models to perform specified tasks), few-shot (i.e. provide contexts and examples in the prompts for the model) and chain-of-thought (CoT), i.e. prompting includes a series of intermediate reasoning steps.

In this paper, preliminary experiments about fine-tuning of GPT models for construction applications will be showcased. One of the objectives is to assess whether fine-tuned GPT models can accomplish a range of tasks with greater accuracy. Pre-training may involve unsupervised learning without labels or annotations. After pre-training, the model can be adjusted for a variety of tasks to increase the quality and accuracy of the text that is produced for that activity, such as language modeling, text categorization, or question-answering. Outcomes of our work include preliminary advice about how knowledge sources must be arranged and how queries can be prompted.

4. POTENTIAL FOR INTEGRATION

This paper discusses the hypothesis that the domain models on which ESs are based can be enriched and expanded through the analysis of relevant scenarios with the help of LLMs, by revealing variables and parameters that are relevant but are currently either excluded from the ES or incorrectly defined in it due to the modeler's bias. Four components are essential to apply such an approach: scenarios, a LLM, an ES and a validation process.

Scenarios: the first step is to identify relevant scenarios that represent real-world situations within the domain of the ES. In this case, the relevant domain is fire safety, and scenarios of fire events are therefore collected. These scenarios should cover a wide range of situations to ensure the system can handle various cases (i.e., different types of fire events). Of particular interest are scenarios that may not occur frequently, but that are still important to handle, as they may reveal aspects that will need to be incorporated into the model of the domain.

LLMS: LLMs can be used to identify patterns, trends, and correlations within the scenarios, thus enriching and expanding the domain model. The process of applying a LLM should be iterative, so that the model can continuously be refined as new scenarios are identified or as the domain evolves. By querying the LLM, different aspects of a scenario can be explored. Each query can build on knowledge gained from the previous queries, allowing the analyst to gradually gain a deeper understanding of the domain. LLMs can challenge existing assumptions and preconceptions, by revealing factors that might have been previously overlooked. They may thus help in avoiding confirmation bias and encourage a more open-minded analysis. Scenarios involving complex interactions between different parameters might be better understood by querying the LLM and exploring how the different factors influence each other. In addition, the analyst can vary certain parameters in the queries to understand how the changes might impact the scenario's outcomes, performing what may be comparable to a sensitivity analysis.

ESs: By repeatedly engaging with a LLM through queries to analyze specific scenarios, the analyst may uncover certain aspects that are otherwise ignored, or that are not well understood. By incorporating those aspects in an existing structured knowledge graph of the ES, the accuracy of the recommendations provided by the ES for such scenarios is increased. This is done by converting the information that is gained into explicit logical statements or rule sets to address varying situations, in a way that represents the real-life decision-making process. The logical statements should be structured in a format suitable for their integration into the existing knowledge graph of the expert system, for example by creating new data fields or modifying existing ones to accommodate the additional information. To account for complex relationships between data in the knowledge graphs, hierarchies of rules can be established, where higher-level rules encompass general scenarios, and lower-level rules handle exceptions and specific cases. This hierarchical structure may support a more detailed and accurate decision-making process.

Validation: The updated knowledge graph of the ES, and the logical statements on which it is based, should be validated by consulting with domain experts, to ensure their accuracy and completeness. Once the enriched knowledge graph is integrated into the existing ES, the system should be thoroughly tested with both previously used and new scenarios to ensure that it performs accurately and reliably. The iterative nature of the process of continuous improvement ensures that the system stays up-to-date and relevant as it learns from new data and insights over time.

To summarize, by enriching and expanding the knowledge graph of an ES through the analysis of relevant scenarios with a LLM, the system can become more robust and capable of supporting informed decision-making in complex real-world situations. By incorporating the aspects uncovered through the querying of a LLM, and defining relevant logical statements, the ES can improve the accuracy of its recommendations for a broader range of scenarios.

5. PROPOSED APPROACH FOR THE USE OF LLMS TO HELP DEFINE SCENARIOS FOR ESS

In the first stage, a LLM is queried that has embedded documents describing scenarios. In GPT (Generative Pre-trained Transformer) models, relevant documents can be embedded to help the model better understand context, and thus improve the accuracy of answers to queries. The embedded documents can be used to fine-tune the GPT model for a specific task. By linking the documents with a query in a single prompt, a unified input is created for the model, allowing it to use the context from the documents to provide more accurate answers to the given queries. Naturally, the quality and relevance of the documents used in the prompt will play a significant role in determining the accuracy of the answers provided, and their selection is therefore crucial.

In the second stage, the answers provided by the LLM are used to enhance the ES. This can be done directly in the ES's knowledge graph, or indirectly through an ontology on which the knowledge graph is based (Figure 1).

The ES's knowledge graphs can be enhanced directly with a set of knowledge units gained from the scenarios by querying the LLM. To do so, the LLMs answers, which are provided in the form of natural language text, must be converted into a structured format that is suitable for their incorporation into the knowledge graph. Typically, entities, relationships, and attributes are extracted from the text, and converted into corresponding nodes, edges, and properties in the knowledge graph, while maintaining the graph's integrity. Depending on the knowledge units that are extracted, existing nodes in the knowledge graph may need to be updated or merged, or new nodes added. Preferably, the newly added knowledge units are linked with the relevant scenarios on which they are based, to maintain traceability and support additional future updates.

Alternatively, the ES's knowledge graph can be enhanced indirectly through an ontology on which it is based. To do so, a semantic ontology needs to be defined and used to create a conceptual bridge between the two systems. This ontology is on the one hand used to define the ES's knowledge graph and is on the other hand repeatedly updated based on the information gained through the interaction with the LLM. The knowledge units, acquired by querying the LLM, are used to define new classes, properties, and relationships in the ontology, thus extending the ontology to better represent the domain. Following this, the ES's knowledge graph is updated based on the extended ontology. Preferably, version control is implemented for the ontology to support the tracking of changes and management of updates. By repeatedly applying the previously described process, the ES can become over time capable of handling a broader range of scenarios with greater accuracy and relevance.

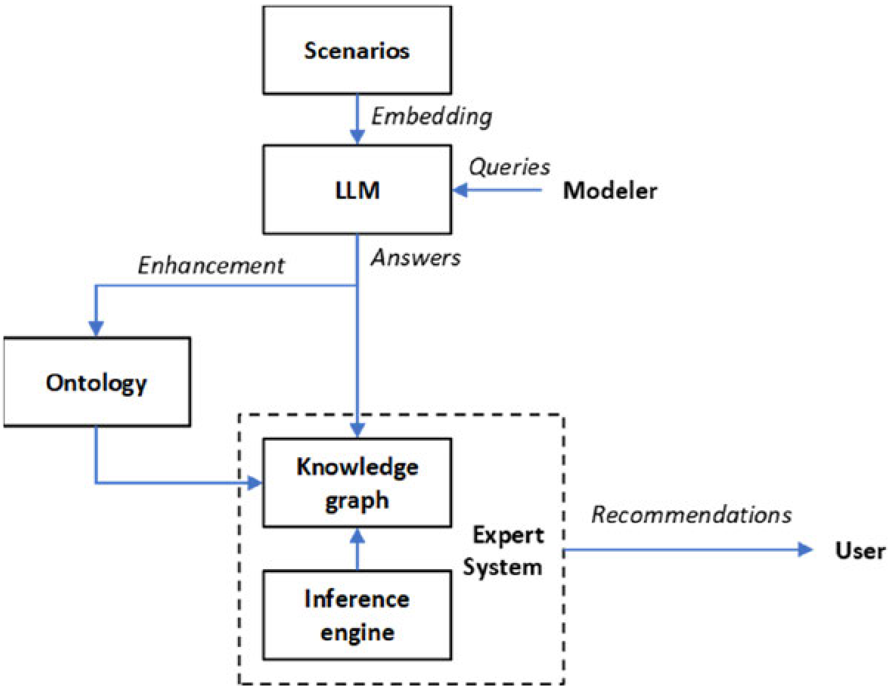

Figure 1: Enhancement of an Expert System using a Large Language Model

6. CHOICE OF THE APPLICATION DOMAIN

The application domain of fire safety planning was chosen for its paramount significance in the building industry and the intricate challenges it poses in safeguarding human life and property from the devastating impacts of fire incidents. Fire incidents in buildings can lead to devastating consequences, including injuries, fatalities, and significant property damage.

By leveraging Large Language Models (LLMs) to systematically analyze reports of real-life fire events, pertinent insights into the factors influencing fire incidents and the efficacy of existing fire safety measures can be extracted. The LLMs provide natural language responses, which can be converted into structured knowledge units suitable for integration into the Expert Systems (ESs) knowledge graph.

Querying reports of fire events and subsequently expanding the ontology based on these queries aligns coherently with the standards set forth by the National Fire Protection Association (NFPA), particularly in Chapter 5, clause 5.5.3. (National Fire Protection Association, 2017). The NFPA emphasizes the criticality of selecting pertinent scenarios, both from predefined options and those deemed relevant by designers, to ensure a comprehensive approach to fire safety planning.

The process of querying, extracting insights, and expanding the ontology facilitates the inclusion of diverse scenarios, encompassing not only common cases but also rare and significant events. The adherence to NFPA standards ensures that the fire safety planning process remains thorough and adaptive, contributing to informed decision-making and improved fire safety strategies in building environments. Consequently, this integration demonstrates the potential to advance knowledge management in the fire safety domain, elevating the overall efficacy of fire safety planning measures.

In the upcoming chapter, a series of tests will be conducted using selected case studies as examples such as, NFPA case study of nightclub fires (Duval, R.F., 2006):

- Rhythm Club, Natchez/Mississippi
- Cocoanut Grove, Boston/ Massachusetts

These case studies, derived from published reports, have been carefully chosen to represent diverse fire safety scenarios encountered in real-world building environments. The adherence to NFPA standards ensures the appropriateness and validity of utilizing published reports for the case studies. These tests will provide valuable insights into the efficacy of the proposed approach, showcasing its potential to enhance knowledge management in fire safety planning and inform more informed decision-making processes.

7. IMPLEMENTATION

To expand the relevant ontology, a modular and contextually aware approach is devised to querying a knowledge corpus for "low temperature" knowledge of a predetermined format, as represented in the ontology. For this, the following components are used.

7.1 Agent-based Methodology

To support the querying of the said corpus, agents will be created and utilized. When creating an LLM-based agent, understanding the nature of the action, or "step" executed by the agent is paramount. The steps can be categorized into:

- User-guided: A user aligns the agent with the target by adding specific information.
- Pre-prompted: The system operates with a generic instruction set to achieve the desired outcome.
- Autonomous: The agent compiles a list of tasks before engaging in user-guided or pre-prompted tasks.

Each of these steps necessitates a mechanism for handling context, as all prompts require appropriate context to yield optimal results. The context influences the stochastic and statistical process of token generation. In this article, we have focused on one step, node querying, which is a pre-prompted step. All steps must be accompanied by the right context. The essence of context handling lies in the creation, storage, and injection of the right bit of context in the proper format (length, form, keywords, wrapping), providing an agent with a solid foundation for action. This mechanism embodies an object-oriented, modular scheme where pre-prompts and context are treated as retrievable objects for injection. These objects are stored in a tree graph, and their predefined format can be utilized for stable injection. Context objects must be designed according to the types of steps and the theme of the project. Each theme presents different objects and relationships, demanding specific syntax to harness hidden semantic information.

The creation of context, being paramount, can be realized through two processes:

- Demanding a Specific Output Format: As part of the agent's response, a certain output format is required for the context object.
- External Ingestion of Information: Utilizing an external mechanism to ingest existing information and represent it in a context object.

As the methodology suggests, the step presented here could be used to continuously enlarge the scope of querying or enable working in parallel on other tasks while offering the right context for them.

7.2 Prompting

To establish the correct behavior for the agent, a system prompt is created first, based on the ontology description and a leading "persona" statement (a role with which the agent's behavior will be aligned).

Example:

```
You are a Fire Evacuation Specialist working with an ontology.

The evacuation of buildings in fire emergency situations is a problem for
which solutions must be found that can help the occupants of these spaces,
guiding them along their route until they are safe. The purpose of the
ontology is to build a knowledge Graph that can contribute to a better
understanding of this topic, as well as to the development of solutions or
systems for the evacuation of buildings more capable of guiding the
occupants of these spaces to a safe place.

Ontology Domain and Scope are:
```

```
Domain: Evacuation of buildings under fire emergency

Focus: Recommendation of evacuation routes in real time based on contextual
information obtained from loT devices.

Contribution: Contributes to a solution for the evacuation of buildings
under fire.

Usage: In fire building evacuation systems.

Purpose: Support interoperability between IoT devices, occupants and other
systems.
```

Next, a ontology python class is created, which is an object-oriented, programming language-resembling representation of an ontology class. The instance can have a description generated for it using the `str` function.

Example:

```
data_property1 = DataProperty("Class_Name", "Property_Name1",
"Description1")

ontology_node = OntologyClass(name="Class_Name", comment="Comment about the
class.", dataproperties=[data_property1, data_property2])
```

The attributes are described as:

```
f"The attribute {self.name} (an attribute to {self.name}) asks:
{self.question}"
```

And the class is then described as:

```
f"The class {self.name} is (are) {self.comment}\nFor finding information to
fill in attributes, consider the following:\n{dataproperties_str}"
```

This representation is used as the "query_node_description".

Next, an example of the "output_format" we demand the agent to follow is given:

```
Formulate your response based on the rule:

1. If you don't know the answer, just respond "Don't know". DO NOT try to
make up an answer.

2. If the question is not related to the context, respond that you are
tuned to only answer questions that are related to the context.

3. DO NOT add anything else to the response.

4. Be clear and precise.

5. Fill the template with information from the context, fill all the
requested data types with information.

Response generic format:

Name: <name>, Description: <description>, Data properties: [<data
properties>]
```

This information is then accompanied by context queried from the knowledge corpus. Texts are extracted from a PDF file and converted into numerical vectors using a specialized PDF processor. This vector representation of the text is stored and then queried using the node description for the retrieval of the top-k results - the context holding the "high-temperature" information.

The augmented prompt is constructed using this formula:

```
Use the following pieces of context to formulate an ontology class instance
representation.

Context:

{context}, {query_node_description}, {output_format}
```

The augmented prompt is then sent to the GPT-4 API for processing and lowering the information's temperature into the required structure.

The above described process will result in the successful curation of information, in a desired structure of one class instance, as it is portrayed in the text. The following are key aspects of the process:

- Data Collection: Utilizing the GPT API to get data from a knowledge corpus to aggregate and accommodate data.
- Knowledge Base Enrichment: Briefly describing the methodology to enrich the knowledge base, including the integration of ontologies, vector handling, and prompt engineering.
- Class Instance Formation: Achieving the structured representation of one class instance from the text, adhering to the defined ontology and prompt templates.

8. CONCLUSIONS

In conclusion, this paper discusses the transformative potential of Large Language Models (LLMs) in Knowledge Management (KM) within the building industry, with a particular focus on fire safety planning. By harnessing the computational prowess of LLMs, a framework is delineated capable of mining unstructured documents from previous projects, processing this data into actionable knowledge, and preserving it for future endeavors.

The challenges for future development of such a framework are multifaceted, and include:

- Accuracy Benchmarking: Creating a mechanism to assess the correctness of the curated information is crucial for ensuring the agent's trustworthiness. This involves evaluating the relevance and consistency of the curated low-temperature information, and employing a back-propagation process to analyze its alignment with the specific domain, ontology, and templates.
- Step Size in Respect of Token Attention Span: The token attention span of the model must be meticulously managed to ensure that the curated information is accurate and properly compiled when augmented into the prompt template. This encompasses careful handling of tokenization, embedding, prompt consciousness, and robust mechanisms for large ontology structures and knowledge corpus.
- Fractured Information Retrieval: Addressing the challenge of incomplete knowledge sources is vital to collect comprehensive information without resorting to premature termination by the model.
- Unwanted Event Amalgamation: Further refinement in the ingestion of PDF files is needed to prevent the creation of class instances that may not be accurately represented in the text.

The outlined challenges, such as accuracy benchmarking and token attention span, underscore the complexities inherent in this approach. Nevertheless, surmounting these hurdles may pave the way for transitioning from labor-intensive curation methods to an automated, intelligent system. This paradigm shift has the potential to change how knowledge is managed in an industry characterized by fragmentation and variability, offering a more streamlined and effective method for capitalizing on past insights to fuel future innovation.

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SCHEDULING OPTIMIZATION OF ELECTRIC READY MIXED CONCRETE VEHICLES USING AN IMPROVED MODEL-BASED REINFORCEMENT LEARNING

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ABSTRACT: *Decarbonizing the construction sector has become an imperative global agenda, with electric machinery playing a pivotal role in realizing this objective. This research concentrates on devising an operational scheduling optimization method for electric ready-mixed concrete vehicles (ERVs) – a groundbreaking, eco-friendly intervention for the construction sector. We commence by outlining a systematic problem definition for the ERV operational process, considering the distinctive characteristics of electric vehicles and ready-mixed concrete (RMC) delivery tasks. The entire process is then conceptualized as a Markov decision problem (MDP), which enables sequential decision-making. We subsequently develop an enhanced model-based reinforcement learning technique, named parallel-masked-decaying Monte Carlo Tree Search (PMD-MCTS), for efficient resolution of the MDP. The entire system is authenticated via a real-world case study, and the PMD-MCTS's performance is juxtaposed against existing benchmarks. The results demonstrate the appropriateness of the proposed MDP formulation for tackling RMC delivery tasks. The PMD-MCTS algorithm and one of its ablation algorithms (PM-MCTS) have demonstrated superior performance compared to other benchmarks in either cost reduction or delay minimization, with PMD-MCTS requiring 30% less computation time than PM-MCTS.*

KEYWORDS: Electric vehicle, Ready-mixed concrete delivery; Scheduling optimization; Model-based reinforcement learning; Monte Carlo Tree Search

1. INTRODUCTION

The escalating issue of carbon emissions, largely attributing to global warming, has necessitated decarbonization as a global imperative for sustainable development (Sinha & Chaturvedi, 2019). As a result, decarbonization has emerged as a global priority for sustainable development (Bogachkova, Guryanova, & Usacheva, 2022). Construction industry activities are a significant source of environmental pollution, responsible for approximately one-third of carbon emissions (Gan, Chan, Tse, Lo, & Cheng, 2017). Specifically, the ready-mixed concrete (RMC) production accounts for a large portion of global emissions (Olanrewaju, Edwards, & Chileshe, 2020). In addition, RMC is a still-growing market due to the rise of green building construction and the urbanization in developing countries (Hart, Nilsson, & Raphael, 1968). Palaniappan, Bashford, Li, Fafitis, and Stecker (2009) indicated that the transportation of RMC represents a major component of energy use and emissions. Therefore, optimizing the scheduling of RMC delivery is crucial for a greener construction industry. Due to the significant development of battery technology and automation, the electric drive technology has been regarded as a promising solution for improving the sustainability of the construction industry (T. Lin et al., 2020). Truck manufacturers have recently developed several electric RMC trucks that aim to implement emission-free transport in the construction industry (*Volvo Trucks delivers the first heavy-duty electric concrete mixer truck to CEMEX*, 2023). However, the academic focus on construction electric vehicles (CEVs), a cross-domain technology integrating the unique properties of electric vehicles (EVs) and the construction industry, has been limited. This research aims to bridge this gap by focusing on the scheduling optimization of electric ready-mixed concrete vehicles (ERV) to further the cause of greener construction.

In the EV domain, several battery-related factors have been extensively studied, such as battery status, charging rates and prices, and charging station locations (Turan, Pedarsani, & Alizadeh, 2020). However, most EV-related studies are not directly applicable to the construction industry due to its unique characteristics and requirements. Furthermore, existing CEV-related studies mainly focus on hardware improvements such as drivetrain (Tong, Jiang, Tong, Zhang, & Wu, 2023) and transmission system (Tan, Yang, Zhao, Hai, & Zhang, 2018), with little attention paid to the management-related topics. Studies related to RMC production and delivery have primarily focused on developing optimization formulations and optimization algorithms. For instance, P.-C. Lin, Wang, Huang, and Wang (2010) formulated the RMC delivery as a job shop problem, where each RMC delivery represents a job operation carried out by one of the trucks that correspond to the workstations. Z. Liu, Zhang, Yu, and Zhou (2017) proposed a time-space network that combines RMC production and vehicle dispatching, and the problem is

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Zhengyi Chen, Changhao Song, Xiao Zhang, Jack Cheng, *Scheduling Optimization of Electric Ready Mixed Concrete Vehicles Using an Improved Model-Based Reinforcement Learning*, pp. 739-750, DOI 10.36253/979-12-215-0289-3.74

optimized by a heuristic algorithm. Nonetheless, these studies overlook the specific properties of ERV, especially those related to the battery, such as charging and energy consumption.

To bridge this gap, our study proposes a scheduling optimization methodology for ERV dispatching. We first provide a detailed problem definition for ERV dispatching, incorporating the unique features of both EVs and RMC delivery tasks. The problem is then modeled as a Markov decision process (MDP) to capture the sequential logic of the RMC dispatching task. Finally, we propose an improved model-based reinforcement learning algorithm to solve the MDP problem. This algorithm, developed using a state-of-the-art Monte Carlo Tree Search (MCTS), is enhanced with a state-dependent action masking and a decaying searching strategy.

2. METHODOLOGY

2.1 ERV Operation Problem Definition

The operation of Electric Ready-mixed Vehicles (ERVs) comprises five components: a) The construction site and b) the ready-mixed concrete (RMC) plant, which are the locations where ERVs are prepared and RMC is poured. c) RMC mixer and d) charging station, which are machinery installed at the RMC plant for loading RMC and charging EVs respectively. Lastly, e) ERVs are the vehicles for dispatching RMC. For the purposes of this study, we assume pumps are pre-installed. The operational process of ERVs can be partitioned into three sections: the in-plant process (IP), the midway process (MP), and the on-site process (OP).

2.1.1 In-plant process

Prior to the delivery of the RMC batch to the construction site, it is imperative that an ERV is adequately prepared with the required RMC and sufficient battery power at the RMC plant. The specificities of two in-plant processes are as follows: **(1) IP1-RMC Production and Loading**: The RMC mixer produces and loads RMC onto ERVs according to the demands, which are typically determined based on the specific requirements of various construction sites. The following assumptions are made: a) RMC mixers can produce any type of required RMC, and the loading rate is set constant in this study for efficient validation. b) The RMC plant can load RMC onto multiple ERVs simultaneously, eliminating any queuing time for the loading (Z. Liu et al., 2017). c) Each ERV should be fully loaded unless it delivers the last batch of the target construction site, which can be smaller than an ERV's capacity. d) The plant owns various types of ERVs, and their loading capacities and operation costs are different (Z. Liu et al., 2017). **(2) IP2-Charging of ERVs**: When an EV's battery is less than its required degree, it will be recharged by charging stations. All the charging stations are installed only in the RMC plant, which is a regular practice in current ERV providers. a) We assume that the charging rates and costs are constant, but a basic cost is set to avoid frequent charging since launching the charging station is power-consuming. b) Multiple ERVs can be recharged simultaneously using multiple charging stations. c) ERVs have different battery capacities, and they can be recharged to a certain level between the existing status and the fully charged status.

2.1.2 Midway process

Following proper preparation, all ERVs should depart from the RMC plant to their corresponding construction sites. Two types of midway processes can be considered: **(1) MP1-Plant to Site**: a) A qualified pump is assumed to be installed on the construction site before the first arrival of ERV. b) To avoid unnecessary battery drainage while waiting with loaded RMC, it is assumed that the ERV will depart only if its arrival time is not earlier than the demand time of the target site. If the arrival time is earlier than the demand time, the ERV's RMC loading time, battery charging time, and travel time will be delayed. c) This study assumes that the ERV has the same traveling speed and battery consumption rate under the loading status. **(2) MP2-Site to Plant**: After unloading a batch of RMC at the construction site, the ERV returns to the plant and prepares for the next delivery batch of RMC. a) It is assumed all RMC have been unloaded, and the ERV is in an empty status. b) All ERVs return with a fixed traveling speed and energy consumption rate in the empty-load status.

2.1.3 On-site process

ERVs are assumed to arrive at the construction site not earlier than the demand time, which allows for the pouring task to commence promptly upon the ERV's arrival. a) Pourings are preferred to be consecutive, but delivery delays are also allowed in real applications. The construction sites claim a maximum for the delivery interval. b) Although static during the pouring process, ERVs remain operational, and a fixed battery consumption rate is assumed. c) This study supposes each construction requires only one ERV for pouring, and the pouring rate is fixed.

2.2 Modeling the ERV Operation Processes via an MDP Model

Based on the ERV operation problem definition, the maximum RMC batch of each construction site can be inferred by considering the minimum ERV capacity and site demands. This allows the ERV operation process to be modeled as a sequential decision-making problem, with the goal of optimizing the dispatch sequence of all the ERVs. During each dispatch, the ERV delivers a batch of RMC to a certain construction site with a certain battery level. Markov Decision Process (MDP) is a potent model-based method for sequential decision-making, which can be solved byiteratively evaluating the reward function for all potential states and actions until convergence to the optimal value (Zhang et al., 2020). Therefore, an MDP formulation is proposed for sequential coverage pattern analysis, represented by a four-element tuple (S, A, Ts,a, Ra). S is the state space, A is the action space, Ts,a is the state transition operator, and Ra is the reward function. These elements are discussed below.

2.2.1 State

S is the state space, $s \in S$ is the current state, which is a tuple of $2N_1 + 2N_2$ components. N_1 denotes the maximum number of ERVs owned by the RMC plant, while N_2 represents the maximum number of construction sites in demand. The MDP state comprises four parts, namely ERV's latest available time (LAT), ERV's battery status, the construction sites' latest demand time (LDT), and the quantities of undelivered RMC. The details of the MDP states are illustrated in Table 1.

Table 1 The definition of the MDP state.

State number	Meaning	Related component	Format
[1, N1]	The latest available time (LAT) of the 1st to the N1th ERVs.	ERV	Day-hour-minutes
[N1+1, 2N1]	The ERVs' battery states on their corresponding LAT.	ERV	kWh
[2N1+1, 2N1+N2]	The latest demand time (LDT) of the 1st to the N3th construction sites.	Construction site	Day-hour-minutes
[2N1+N2+1, 2N1+2N2]	The quantities of undelivered RCM for a certain construction site.	Construction site	m3

For clarification, we consider a scenario with two ERVs, two construction sites, and the state is (9:00, 9:30, 120, 60, 10:30, 12:00, 50, 25) (as shown in Fig. 1). It means that the first ERV is available after 9:00 with a 120-kWh battery, and the second ERV is available after 9:30 with a 60-kWh battery. The first construction site has a latest demand time (LDT) of 10:30 and requires 50 m^3 of RMC. The second construction site has an LDT of 12:00 and requires 25 m^3 of RMC.

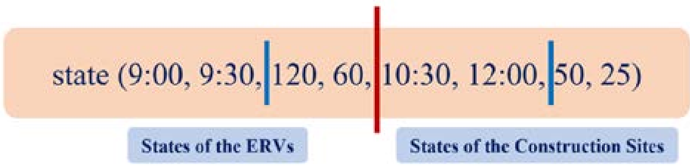

Fig. 1 An illustration of the MDP state

2.2.2 Action

A is the action space, where $a \in A$ is the action taken based on the current state. Each action is denoted by (*e*, *c*, *b*), where *e* is the serial number of the ERV, *c* is the serial number of each construction site, and *b* is the departure battery level. For the battery level, 0 means that the battery is kept unchanged, and its accuracy can be determined based on the user's computational capacity. Following the same scenario in section 3.3.1, we assume a battery accuracy is 5. Then, action (1, 2, 4) means the first ERV deliveries a batch of RMC to the second construction site with an 80-percentage battery, and action (2, 1, 0) means the second ERV is dispatched to the first construction site without charging.

2.2.3 Transition

$\boldsymbol{T_{s,a}}$ is the absolute transition that action *a* in state *s* at step *t* will lead to state *s*' at step *t+1*, as the transition is fully under control in this study. Apart from the state information, additional parameters are clarified for the state transition (Table 2).

Table 2 Fixed parameters for the state transition.

Fixed Parameters	Definition	Related element	Unit
l	The RMC loading rate of the mixer.	RMC mixer	m^3/min
p	The power of the charging station.	Charging station	kw
$g[e]$	The battery capacity of an electric vehicle	ERV	kWh
x	The battery accuracy	ERV	/
$m[e]$	The RMC capacity of the e^{th} ERV.	ERV	m^3
v_1	The vehicle speed of loading status.	ERV	km/hr
v_2	The vehicle speed of empty status.	ERV	km/hr
r_1	The battery consumption rate for the ERVs to travel under loading status.	ERV	%/km
r_2	The battery consumption rate for the ERVs to travel under empty status.	ERV	%/km
r_3	The battery consumption rate for ERVs to conduct the pouring task.	ERV	%/m^3
$d[c]$	The distance from the plant to the c^{th} construction site.	Construction site	km
w	The RMC pouring rate.	ERV	m^3/min

Firstly, the quantity of the RMC required by the target construction site ($s[2N_1 + N_2 + c]$) is compared with the capacity of the ERV ($m[e]$) to get the quantity of delivered RMC $RMC_{deliveried}$ (Eq.(1)). Subsequently, the loading time $t_{loading}$ can be obtained by Eq.(2). Given the action component b and the battery status ($s[N_1 + e]$), the charging time $t_{charging}$ can be calculated using Eq.(3). The departure time from the factory to the construction $t_{departure}$ can be determined by Eq.(4). Based on Eq.(5), the start time of the current dispatch t_{start} can be obtained by comparing the ERV's arrival time ($s[e] + t_{charging} + t_{loading} + t_{departure}$) with the construction site's LDT ($s[2N_1 + c]$). Further, Eqs.(6) and (7) are used to calculate the pouring time $t_{pouring}$ and return time t_{return}.

$$RMC_{deliveried} = \min(s[2N_1 + N_2 + c], m[e]) \quad (1)$$

$$t_{loading} = RMC_{deliveried}/l \quad (2)$$

$$t_{charging} = (\frac{b}{x} * g[e] - s[N_1 + e])/p \quad (3)$$

$$t_{departure} = d[c]/v_1 \quad (4)$$

$$t_{start} = \min\left(s[e] + t_{loading} + t_{charging} + t_{departure}, s[2N_1 + c]\right) \quad (5)$$

$$t_{pouring} = RMC_{deliveried}/w \quad (6)$$

$$t_{return} = d[c]/v_2 \quad (7)$$

The LAT of the current ERV $s[e]$ is updated by adding the pouring time and return time to the start time (Eq.(8)). The ERV's battery level $s[N_1 + e]$ is updated according to Eq.(9), where the second term is the battery consumption during traveling, and the third term is the battery consumption during the pouring task. The target construction site's LDT $s[2N_1 + c]$ is updated by adding the pouring time to the start time (Eq.(10)). Further, the required quantity of RMC $s[2N_1 + N_2 + c]$ can be updated by subtracting the quantity of delivered RMC from the target construction site's initial requirement, as shown in Eq.(11).

$$s[e] = t_{start} + t_{pour} + t_{return} \quad (8)$$

$$s[N_1 + e] = \left(\frac{b}{x} - d[c] * (r_1 + r_2) - RMC_{deliveried} * r_3\right) * g[e] \quad (9)$$

$$s[2N_1 + c] = t_{start} + t_{pour} \quad (10)$$

$$s[2N_1 + N_2 + c] = s[2N_1 + N_2 + c] - RMC_{deliveried} \quad (11)$$

2.2.4 Reward

R_a is the immediate reward of action *a*. In the RMC dispatch task, the objective of the RMC plant is to minimize the operational costs and adhere to the dispatch rules, such as avoiding exceeding the maximum pouring interval. Meanwhile, the construction sites aim to minimize the total delay for the pouring task. Therefore, the total operation costs r_c and the dispatch delay r_d are selected as the two primary reward components. r_c can be calculated by Eq.(12). c_1 ($/min) is the unit cost of the ERV operation, c_2 ($) is the fixed cost of opening the charging station, which aims to avoid frequent charging, and c_3 ($/kWh) is the unit price for ERV charging. The relevant costs of RMC production are not considered as the quantity of the RMC demand is fixed. According to Eq (13), r_d can be calculated by comparing ERV's arrival time with the construction site's LDT.

$$r_c = -c_1[e] * (t_{loading} + t_{charging} + t_{departure} + t_{pouring} + t_{return}) - c_2 * Boolean(t_{charging} > 0) - c_3 * (\frac{b}{x} * g[e] - s[N_1 + e]) \quad (12)$$

$$r_d = -\max(s[e] + t_{charging} + t_{loading} + t_{departure} - s[2N_1 + c], 0) \quad (13)$$

In addition, a significant negative reward r_p is generated if an invalid action is taken. Three types of invalid actions have been identified: 1) Actions that head to the construction site without any demand for RMC, as shown in Eq.(14); 2) Actions with a battery level below the current battery level or the minimum battery requirement (Eq.(15)). 3) Actions that result in a dispatch delay that exceeds the maximum interval δ (Eq.(16)). When the RMC demands of all the construction sites are fulfilled, a great positive reward r_f is generated. Finally, the total reward can be calculated by Eq.(17), where α_1 and α_2 are importance hyper-parameters. Apart from r_f, all other reward components are negative.

$$\boldsymbol{InvalidAction\ 1}: s[2N_1 + N_2 + c] > 0 \quad (14)$$

$$\boldsymbol{InvalidAction\ 2}: b > \max(s[N_1 + e], d[c] * (b_1[e] + b_2[e]) - RMC_{deliveried} * b_3[e]) \quad (15)$$

$$\boldsymbol{InvalidAction\ 3}: s[e] + t_{charging} + t_{loading} + t_{departure} - s[2N_1 + c] \le \delta \quad (16)$$

$$r = r_f + \alpha_1 * r_c + \alpha_2 * r_d + r_p \quad (17)$$

2.3 Optimization Using PMD-MCTS

Many reinforcement learning methods have been developed to solve the MDP problem, including model-free algorithms and model-based algorithms (Sutton & Barto, 2018). Specifically, the model refers to the state transition function $T_{s,a}$ and the reward function R_a of the MDP problem. Compared with model-free methods, model-based reinforcement learning has the great potential to make RL algorithms more sample efficient (Wang et al., 2019). MCTS is a model-based RL algorithm that plans the best action at each time step (Browne et al., 2012). It is an effective heuristic search algorithm for solving episodic decision-making problems when the underlying search spaces are computationally expensive (B. Huang, Boularias, & Yu, 2022). However, MCTS relies on a large number of interactions with the environment emulator to construct the search trees for decision-making (Browne et al., 2012). To mitigate the high time complexity of classical MCTS, this section develops an improved MCTS algorithm， named parallel-masked-decaying MCTS (PMD-MCTS). Specifically, the state-of-the-art parallel MCTS algorithm, WU-UCT (A. Liu et al., 2018), is adopted as the fundamental model. It is further improved by incorporating a state-dependent action masking operation and a decaying search strategy. The details of the algorithm are introduced as follows.

2.3.1 Fundamentals of WU-UCT-based parallel Monte Carlo Tree Search

MCTS adopts a tree-search method that incrementally extends a search tree from the current environment state (Luo et al., 2022). Each node denotes a visited state, and each edge from this state denotes an action that can be taken at that state, leading to a landing node that denotes the state after the transition. Typically, MCTS performs four sequential steps repeatedly: selection, expansion, simulation, and backpropagation (Fig. 2 (a)). The selection step starts from the root node (current state) and recursively selects an existing child node according to a tree policy. The process ends when it reaches a leaf node or other termination conditions. One of the most commonly used node-selection policies is the Upper Confidence bound for Trees (UCT), and the UCT value a_s can be calculated by Eq.(18). Here, *C(s)* represents the child node set of the current node *s*; $V_{s'}$ is the average value estimation for a certain child node s', denoting the exploitation; The second term is the uncertainty of the value estimation, denoting the exploration. N_s and $N_{s'}$ denote the number of times that nodes s and s' have been visited, while β is the factor that controls the trade-off between exploitation and exploration. During the expansion state, a new child node is added to the selected node, and the value of the expanded node is estimated by performing a model-based simulation until termination. The simulation process follows a certain policy (e.g., random). Finally, backpropagation recursively updates the statistics $\{V_s, N_s\}$ from the expanded node to the root node along the selected path. According to Eq.(19), the visit count of each node is increased by 1. The latest value estimation of each node can be obtained by Eq.(20), where γ is the reward discount factor, and a_t is the action that turns the state s_t to the state s_{t+1}. It should be noted that the leaf node s_T obtains its value from the simulation step. Finally, each node's average value estimation is updated according to Ep. (21).

$$a_s = \underset{s' \in C(s)}{\operatorname{argmax}} \left\{ V_{s'} + \beta \sqrt{\frac{2 \log N_s}{N_{s'}}} \right\} \tag{18}$$

$$N_{s_t} = N_{s_t} + 1 \tag{19}$$

$$V'_{s_t} = R(s_t, a_t) + \gamma V'_{s_{t+1}} \tag{20}$$

$$V_{s_t} = \left(\left(N_{s_t} - 1\right) V_{s_t} + V'_{s_t}\right) / N_{s_t} \tag{21}$$

Parallelizing MCTS over multiple workers is an efficient method to improve the optimization speed. During the parallel computation, workers typically operate at different steps as the simulation and expansion processes are slow (Fig. 2 (b)). As a result, the update of statistics $\{V_s, N_s\}$ may become outdated for workers, and the statistics loss becomes inevitable. However, the latest N_s is available as soon as a worker initiates the computation since we only need to know if the node is selected. Therefore, the WU-UCT algorithm partially addresses the information loss by introducing another quantity O into the classical UCT (Eq.(22)), which counts the number of computations that have been initiated but not completed (light dashed blue lines in Fig. 2 (b)). The updated UCT effectively balances exploration-exploitation tradeoff by considering incomplete samples, and the node values can be updated according to Eqs.(23) and (24).

$$a_s = \underset{s' \in C(s)}{\operatorname{argmax}} \left\{ V_{s'} + \beta \sqrt{\frac{2 \log (N_s + O_s)}{N_{s'} + O_{s'}}} \right\} \tag{22}$$

$$\text{Incomplete update:} \quad O_s = O_s + 1 \tag{23}$$

$$\text{Complete update:} \quad O_s = O_s - 1, \quad N_s = N_s + 1 \tag{24}$$

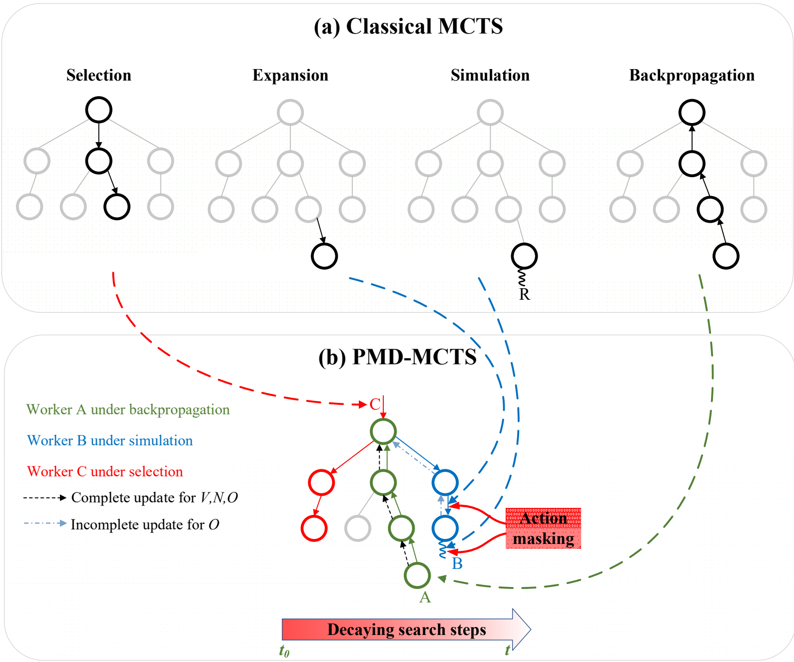

Fig. 2 The relationship between classical MCTS and PMD-MCTS

2.3.2 Action masking

The ERV operation involves complicated rules, and the valid action spaces usually vary under different states. Typically, RL algorithms sample the action from a space containing actions of all states and assign a significant negative reward for invalid actions. However, this kind of invalid action penalty is challenging to explore, particularly when the state is complicated, even for the very first reward (S. Huang & Ontañón, 2020). Hence, this section proposes a state-dependent action masking method to improve MCTS's efficiency (Fig. 2 (b)). First, a complete action space A_0 is generated, which contains all combinations of the ERV's serial number, each construction site's serial number, and the departure battery level. Then, invalid actions (Eqs.(14)-(16)) of A_0 are updated under each state (circles in Fig. 2 (b)), followed by invalid action masking. Specifically, $V_{s'}$ (Eq.(22)) of invalid actions are set as a large negative number M (e.g., $M = -1 \times 10^8$) during the expansion stage. Consequently, only valid actions will be expanded. During the simulation stage, actions are randomly selected from valid candidates, while invalid ones are ignored. In practical implementations, vectorization is adopted for speeding up the masking operations.

2.3.3 Decaying search strategy

During the implementation of MCTS, an initial MDP state is set as the start for optimization. The best child node of the current state is set as the output when the number of iterations is larger than a threshold value of N_δ. Then, the updated state becomes the new start, and the process iteratively continues until the MDP ends. Intuitively, the size of the Monte Carlo tree will decrease gradually, as the quantity of undelivered RMC decreases. Hence, the last stages of MDP may not require many iterations, and this section proposes a decaying threshold to ensure both optimization accuracy and efficiency. The decaying strategy is designed based on the remaining demand for RMC, as shown in Eq.(25). $N_{\delta 0}$ is the maximum number of iterations determined by the users, Q_{left} is the remaining required quantity of RMC, Q_{left} is the total RMC demand, and e is the Euler's number.

$$N_\delta = N_{\delta 0} * \frac{e^{\frac{Q_{demand}}{Q_{total}}}}{e} \tag{25}$$

3. VALIDATION

3.1 Scenario Setup

As the use of electric RMC vehicles is a relatively new solution in the construction industry, a customized dataset for this purpose is currently unavailable. Therefore, it is reasonable and acceptable to utilize data from previous RMC delivery studies to establish the proposed MDP model. Hence, we extracted the basic configurations of sites and RMC vehicles from the dataset of (Z. Liu et al., 2017). The dataset was determined based on a real case, including distances between the sites, RMC demands of the construction sites, RMC loading rate, ERVs' capacities, and relevant costs. We updated certain assumptions from (Z. Liu et al., 2017) in more detail. For example, we provided vehicle speeds for traveling time calculation and determined the battery-related factors based on actual reports (e.g., the charging rates). Table 3 describes the shared parameters, Table 4 indicates the information on the construction sites, and Table 5 shows ERV information. Two objectives are optimized: a) objective 1 aims to minimize the operation costs for the RMC plant, and b) objective 2 aims to minimize the dispatch delay for the construction sites.

Table 3 Information of the shared parameters.

Shared parameters	Value	Unit
RMC loading rate	2	min/m^3
Battery charging power	20	kw
Battery accuracy	5	/
Vehicle speed of loading status	40	km/hr
Vehicle speed of empty status	80	km/hr
Battery consumption rate for ERVs to travel under loading status	1	%/km
Battery consumption rate for ERVs to travel under empty status	0.8	%/km
Battery consumption rate for ERVs to conduct the pouring task	0.25	%/ m^3
RMC unloading rate	0.5	m^3/min
Cost of opening the charging station	5	$
Unit cost for ERV charging	2	$/kWh
Importance hyper-parameters α_1	1 for objective 1, 0 for objective 2	/
Importance hyper-parameters α_2	0 for objective 1, 1 for objective 2	/
Reward for an invalid action r_p	-1000	/
Reward for completing the task r_f	1000	/
Maximum pouring interval δ	90	min

Table 4 Information of the construction sites.

No.	RMC demand (m^3)	Distance (km)	Start time (hr:mm)
C1	6	6.2	8:30
C2	60	4.0	8:40
C3	26	5.5	9:30
C4	3	3.4	10:40
C5	64	12.0	11:20
C6	64	4.1	10:00
C7	24	6.6	15:10

Table 5 Information of the ERVs.

No.	1	2	3	4	5	6	7	8
RMC Capacity (m^3)	8	8	8	7	7	6	5	2
Unit cost ($/min)	1.3	1.3	1.3	1.2	1.2	1.1	1.0	0.8
Battery capacity (kWh)	160	160	160	160	160	120	100	50
Initial battery capacity (kWh)	80	80	80	80	80	60	50	25
Initial LAT (hr:mm)	6:00	6:00	6:00	6:00	6:00	6:00	6:00	6:00

3.2 Benchmark Setup

To validate the performance of our proposed PMD-MCTS algorithm under the given scenario setup, we compared it with three benchmarks, including GA-based optimization from (Z. Liu, Zhang, & Li, 2014), and two ablation studies. All algorithms were run ten times to minimize the impact of random errors. The two most common metrics, namely a) the average reward and b) the average computation speed, were used as the first two evaluation criteria. To test the stability of the algorithm, three additional metrics were selected, namely c) the success rate, d) the standard deviation (SD) of the average reward, and e) the SD of the average computation speed. Instead of terminating the MDP process when an invalid action occurs, we adopted a great negative number as a penalty and continued the MDP simulation. To avoid a negative battery state, the negative battery level was modified to the smaller one between the current battery status and the minimal battery requirement.

3.2.1 Genetic algorithm

Three-layer chromosome: The chromosome structure was designed based on the concepts of (Karakatič, 2021; Z. Liu et al., 2014). As described in (Z. Liu et al., 2014), the maximum number of vehicles to be dispatched is fixed, which is set as the chromosome length. The chromosome of (Z. Liu et al., 2014) has three layers: a) sequence of construction site ID, b) sequence of the accumulative number of vehicles to the construction site, and c) sequence of vehicle ID. The second layer was removed as it can be inferred from the first layer. In addition, we added a layer for battery level according to (Karakatič, 2021), and used the same battery definition as our PMD-MCTS method. An illustration of the chromosome is shown in Fig. **3**.

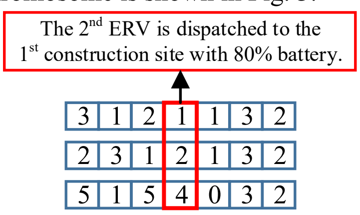

Fig. 3 An illustration of the GA chromosome

Selection: The chromosome represents a set of sequential MDP actions that can be input into the MDP model to obtain the accumulative reward (fitness). It should be noted that action will not be taken if the target construction site has been satisfied.

Crossover: This study adopted one-point crossover, but the crossover operation may change the maximum number of vehicles required by each site. Hence, the probability mapping method of (Z. Liu et al., 2014) was adopted for the first layer crossover, as shown in Fig. **4**. Specifically, each gene in the first layer has a mapping probability, and the crossover is conducted on the probability layer. The new chromosome is generated by mapping the probabilities to a basic chromosome in descending order, and the basic chromosome can be user-defined ([1,1,1,2,2,3,3] in Fig. **4**). The crossovers of the second and third layers are conducted directly. We conduct the crossover layer by layer, which can generate six children during one crossover.

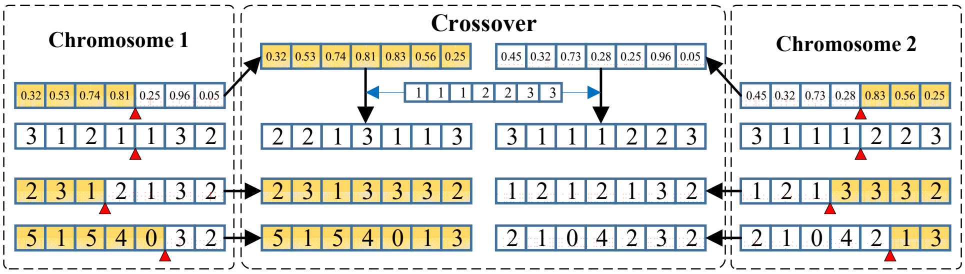

Fig. 4 The crossover of two chromosomes

Mutation: One-point mutation is adopted, as shown in Fig. **5**. Similar to the crossover operation, the mutation of the first layer is realized by probability mapping, while the genes in the other two layers are mutated according to their ranges.

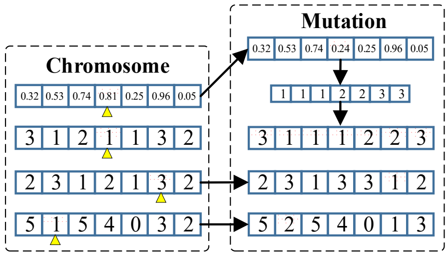

Fig. 5 The mutation of the chromosome

Table 6 Hyperparameters of genetic algorithm

Hyperparameters	Value
Population size	20
Parent number	3
Mutation rate	0.3
Maximum generation number	200000

3.2.2 Ablation studies

We have made two improvements based on WU-UCT-based MCTS. To evaluate the effectiveness of these improvements, we conducted two ablation studies: a) PD-MCTS, which is PMD-MCTS without action masking, and b) PM-MCTS, which is PMD-MCTS without decaying search strategy. The hyperparameters used in the MCTS algorithms are listed in Table 7.

Table 7 Hyperparameters of MCTS algorithms

Hyperparameters	Value
Number of expansion workers	8
Number of simulation workers	16
Maximum search step ($N_{\delta 0}$)	3000
Maximum search depth	100
Maximum search width	200
Discount factor	0.9
Expansion policy	Random

3.3 Results

Experiments for PMD-MCTS and four benchmark algorithms were conducted on the designed scenario. The entire procedure was executed on a laptop with the specification of Intel i9-10980H 3.10GHz CPU and 32GB RAM. The the scheduling performance of each algorithm is shown in Table 9 and Table 8.

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Table 8 Scheuling performance of each algorithm in objective_1 (minimizing the costs)

	Average reward	SD of average reward	Success rate (%)	Average computation time (s)	SD of average computation time
GA	-8313.1(-6494.3*)	1283.1	0	102.0	**1.7**
PD-MCTS	-6950.0 (-5421.5*)	1040.6	0	320.8	26.3
PM-MCTS	-3095.2 (-3004.5*)	**120.4**	**100**	385.6	40.1
PMD-MCTS	**-3064.0 (-2862.4*)**	123.0	**100**	260.0	19.9

Table 9 Scheuling performance of each algorithm in objective_2 (minimizing the delay)

	Average reward	SD of average reward	Success rate (%)	Average computation time (s)	SD of average computation time
GA	-837.9 (479.4*)	1076.5	30	93.27	2.0
PD-MCTS	-484.1 (182.8*)	503.3	**100**	497.8	78.1
PM-MCTS	969.0 (1000*)	18.2	**100**	292.4	10.4
PMD-MCTS	**991.6 (1000*)**	**6.7**	**100**	203.0	**1.6**

* indicates the optimal performance

The empirical results indicate that our PMD-MCTS algorithm demonstrates superior performance, achieving the highest rewards across both objectives. Specifically, the average reward of the PMD-MCTS in objective 1 is 3064.0, which translates to an average cost of $4064.0. In objective 2, the average reward of the PMD-MCTS is 991.6, representing an average delay of 8.4 minutes, and the most optimal solution can eliminate any delay entirely. Furthermore, our findings suggest that only algorithms implementing action masking (i.e., PMD-MCTS and PM-MCTS) can consistently ensure a feasible solution for both objectives. These two algorithms also display the smallest standard deviation of average reward, indicating their superior stability. Although PM-MCTS exhibits a performance similar to PMD-MCTS in terms of reward and success rate, the PMD-MCTS requires 30% less computational time than PM-MCTS.

4. DISCUSSIONS

This study's outcomes substantiate the effectiveness of our proposed scheduling optimization approach for managing ERV operations. This methodology mainly contributes to the field in three ways.

Firstly, this study addresses an existing gap in on-road Commercial Electric Vehicle (CEV) research. We are pioneers in examining CEVs, particularly on-road CEVs, marking a significant stride towards sustainable advancement in the construction sector. By incorporating the demands of Ready-Mixed Concrete (RMC) dispatching and Electric Vehicles (EVs), we have holistically examined the characteristics of ERVs. This problem definition can potentially be extrapolated to other CEV studies in the future. Secondly, we have crafted a novel formulation for the RMC delivery problem, utilizing the Markov Decision Process (MDP) based on the temporal dynamics of the RMC delivery process. Compared to its predecessors, the MDP formulation is a more rational choice as it facilitates sequence decision-making. This approach prevents invalid decisions at each stage and ensures the decision-making process is far-sighted, considering all decisions in a comprehensive manner. Lastly, we introduced an enhanced Monte Carlo Tree Search (MCTS) algorithm, named PMD-MCTS, to optimize the ERV operation process. When compared with four benchmark algorithms, it proved to be the most effective. Two key advantages of the PMD-MCTS were identified: Both PMD-MCTS and PM-MCTS displayed superior performance in terms of average reward and success rate, outperforming the Genetic Algorithm (GA) by employing the MCTS optimization strategy. The GA algorithm fails to ensure a feasible solution for both objectives, owing to its limitations in managing sequential requirements. PMD-MCTS surpassed PM-MCTS on computational speed. Our PMD-MCTS saves over 30% of the computational time required by PM-MCTS, without compromising on accuracy, by implementing a decaying strategy.

5. CONCLUSION

In the face of pressing concerns over carbon emissions, the construction industry can expect to see an influx of more sustainable technologies. Electric Ready-mixed Vehicles (ERVs) are a promising technology geared towards enhancing the sustainability of the construction industry. However, the interdisciplinary nature of ERVs has led to a considerable gap in this field. This study addressed this gap by proposing a scheduling optimization methodology for ERV dispatching. It introduces a systematic problem definition for the ERV operation, which integratively considers the properties of both EVs and RMC delivery tasks. Moreover, the ERV operation process is modelled as an MDP problem, thereby breaking down the entire process into sequential sub-processes. The proposed PMD-MCTS algorithm, equipped with parallel computing, invalid action masking, and decaying searching capability, has been validated through a meticulously designed experiment. This study, thus, provides a comprehensive evaluation of ERV operations and offers a solid foundation for future research in this domain.

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TESTING CHATGPT-AIDED SPARQL GENERATION FOR SEMANTIC CONSTRUCTION INFORMATION RETRIEVAL

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ABSTRACT: *Recently there has been a strong interest in using semantic technologies to improve information management in the construction domain. Ontologies provide a formalized domain knowledge representation that provides a structured information model to facilitate information management issues such as formalization and integration of construction workflow information and data and enables further applications such as information retrieval and reasoning. SPARQL Protocol And RDF Query Language (SPARQL) queries are the main approaches to conduct the information retrieval from the Resource Description Framework (RDF) format data. However, there is a barrier for end users to develop the SPARQL queries, as it requires proficient skills to code them. This challenge hinders the practical application of ontology-based approaches on construction sites. As a generative language model, ChatGPT has already illustrated its capability to process and generate human-like text, including the capability to generate the SPARQL for domain-specific tasks. However, there are no specific tests evaluating and assessing the SPARQL-generating capability of ChatGPT within the construction domain. Therefore, this paper focuses on exploring the usage of ChatGPT with a case of importing the Digital Construction Ontologies (DiCon) and generating SPARQL queries for specific construction workflow information retrieval. We evaluate the generated queries with metrics including syntactical correctness, plausible query structure, and coverage of correct answers.*

KEYWORDS: *Semantic web, Ontology, ChatGPT, SPARQL, RDF, Information retrieval, Construction*

1. INTRODUCTION

Construction is an information-intensive and dynamic industry, which requires effective information management and exchange. Especially, construction professionals need always to retrieve demanding information about the construction process to be aware of the prompt situation to support their decision-making and action-taking (Akinci, 2015). With the ongoing advancements of digital implementation in the construction domain, a large amount of semantic data can be collected from heterogeneous systems, which requires a systematic solution to formalize, integrate, and manage the data (Kosovac et al., 2000). Therefore, researchers in the construction domain have investigated the application of semantic web technologies to facilitate information formalization and interoperability issues (Zhou et al., 2016). For example, numerous ontologies have been developed in the construction domain, to provide a formalized construction domain knowledge representation and comprehensive semantic vocabulary. These ontologies support the conversion of construction information into Resource Description Framework (RDF) format and the establishment of an integrated semantic graph database.

Such integrated semantic graph database has been proven to the advantageous in the application of information integration, reasoning, and retrieval by academic scholars in the construction domain (Akinyemi et al., 2018). However, in terms of the practical implementation, one drawback of the graph database can be identified. To retrieve the demanding information from the graph database, the SPARQL Protocol and RDF Query Language (SPARQL) queries are needed. However, the construction sector has limited practitioners with sufficient knowledge of ontology and proficient skills to code the SPARQL queries at the moment. This makes it difficult for end-users to interact directly with the graph database and retrieve the particular construction information they need. While there have been various attempts to employ web-based lists or templates to assist users in crafting SPARQL queries without coding skills, generating SPARQL queries quickly and easily remains a challenge for end-users. Given this challenge, it would be beneficial to develop an intuitive and self-explanatory method that allows end-users to create SPARQL queries more easily.

ChatGPT is an AI-empowered language generation model, which uses the Transformer algorithm and large language model (LLM) principle as the basis to generate human-like text based on the given prompts and context

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Yuan Zheng, Olli Seppänen, Sebastian Seiß, Jürgen Melzner, *Testing ChatGPT-Aided SPARQL Generation for Semantic Construction Information Retrieval,* pp. 751-760, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.75

with rapid response time (van Dis et al., 2023). After its public release at the end of 2022, ChatGPT received huge attention from academia, industries, and consumers. ChatGPT also can analyze and generate structured syntax-based contents such as codes, scripts, and ontology syntax (Lin et al., 2023). ChatGPT can also generate the SPARQL query sentences based on the predefined ontology inputs since its database involves numerous examples of SPARQL and ontologies in the OWL representation (Tan et al., 2023). Based on this feature, using ChatGPT could be considered to be an alternative approach for information retrieval for the RDF data, which would be easy and simple to use. ChatGPT can also be used to directly retrieve information from a provided ontology, including instance data, without using SPARQL queries. However, due to the private and sensitive nature of company and construction-related instance data, it is imperative not to share this kind of data with a self-learning LLM model.

However, the accuracy and real capability of ChatGPT to generate practical SPARQL queries for achieving specific information retrieval in the construction domain have not been tested. To assess whether if it is a feasible solution to aid construction information retrieval tasks, in this paper, we aim to test and evaluate the current capability of ChatGPT to generate the SPARQL queries for accomplishing domain-specific construction information retrieval tasks. The Digital Construction Ontologies (DiCon) (Zheng et al., 2021) previously developed by our research group is used as a case study for the test. We first feed the DiCon ontologies to the ChatGPT for the initial ontological parse as the fundamental context of generating the SPARQL queries. We experimented on the generated SPARQL with four different scenarios and used the metrics of syntactical correctness, plausible structure, and the coverage of the correct result to assess the generated SPARQL queries.

The paper is structured as follows. Section 2 provides a review of related works of ontologies and ChatGPT. Section 3 introduced the research methodology and the architecture of the DiCon-ChatGPT system. In Section 4 the tests and results are illustrated. This is followed by the discussion, limitation, and future research in Section 5. Finally, in section 6 the conclusion of the paper is given.

2. BACKGROUND

2.1 Semantic Web and construction information

Data and information are the key resources of the construction industry to guarantee smooth collaboration for the operations. However, data and information are also influenced by the segmented nature of the construction industry and the diverse software solutions in use. The data is generated in isolated systems by the different stakeholders in the different disciplines and is usually formed into various file formats (Kosovac et al., 2000). Such interoperability issue is notorious in the construction domain. The semantic web and associated Linked Data concept is considered as an approach to facilitate the information interoperability problem, which provides technical standards for a comprehensive heterogeneous information integration and machine-readable representation of the data for further implementation (Beetz et al., 2021).

Ontologies serve as the foundation of the semantic web, which provides a shared and machine-readable conceptualization of domain knowledge and could be further used as a data structure to formalize and integrate data and information. Recently, ontologies have become increasingly relevant in the construction domain, to address challenges like data integration and knowledge management (Pauwels et al., 2017). Various iconic domain ontologies have been created in the construction field, including generic ones like e-COGNOS (El-Diraby et al., 2011) and IC-PRO-Onto (El-Gohary et al., 2010). Our research team also developed the DiCon, which defines construction workflow-related entities with the Semantic Web Ontology Language (OWL) representation and achieves integrating data from diverse systems. DiCon also aligned with other ontologies such as IFCOWL (Pauwels, 2016), the Building Topology Ontology (BOT) by Rasmussen et al. (2020), and SOSA/SSN ontology (Janowicz et al., 2019) to link the construction information with building information modeling, topological, and sensor data.

The foundational language of the semantic web is the Resource Description Framework (RDF). The data structure of RDF is organized into a triple format of a subject, predicate, and object, or subject, property, and value (Manola et al., 2004). The RDF triples constitute an RDF graph and store it in RDF graph stores for further utilization such as information retrieval (Hitzler et al., 2008; Allemang et al., 2020). SPARQL Protocol and RDF Query Language (SPARQL) is a semantic graph query language specifically designed to query RDF data (W3C, 2013). SPARQL allows users to query RDF data by specifying patterns to match against the triples in the RDF graph. Utilizing an RDF-based ontology together with SPARQL can significantly enhance the efficiency of information extraction.

2.2 ChatGPT and related works

ChatGPT is a state-of-art large language model (LLM) developed by OpenAI. The G to refers to generative, which means the ability to generate human-like responses and demonstrate a level of language understanding that has been groundbreaking in the field of natural language processing. P refers to pre-trained because the model is pre-trained on a massive dataset containing a diverse range of text from the internet. The T refers to Transformer, the architecture of a deep-learning model designed for natural language processing tasks (van Dis et al., 2023). It learns to predict the next word in a sentence, which enables it to understand grammar, context, and semantics in the text. Currently, ChatGPT has four versions, including GPT-1, GPT2, GPT3.5, and the latest GPT4.

As an AI language model, ChatGPT's responses are based on patterns learned from a diverse range of data during training, which includes general information on ontologies, SPARQL, and RDF. Therefore, ChatGPT also can collaborate with Semantic Web technologies. Several scholars have explored the combination of ChatGPT with semantic web technologies in different directions. Lin et al. (2023) involved context-based ontology modeling with ChatGPT to represent database semantics in natural language representation for supporting database management in data integration. Tan et al. (2023) assessed the capability of ChatGPT to conduct knowledge-based question-answering with generated SPARQL queries. The experimental results showed that ChatGPT is a promising tool for question-answering under continuous updating and iterating of the model. Meyer et al. (2023) conducted a set of experiments using ChatGPT with the knowledge of graph engineering. The result showed ChatGPT has a remarkable capability to support knowledge graph engineering in constructing knowledge graphs, translating natural language queries into precise and organized SPARQL queries, tailored to the provided knowledge graphs, and diagrams illustrating expansive schemas of knowledge graphs.

In summary, the existing tests indicate that ChatGPT can generate SPARQL queries for information retrieval tasks. Therefore, ChatGPT could be a potential tool for the automated generation of SPARQL queries for construction information retrieval and management. However, the previous related works focus on assessing the capability of ChatGPT in general Linked Data and knowledge graph domains. The capability of ChatGPT to generate domain-specific SPARQL queries for construction information retrieval has not been explicitly tested or validated. Therefore, in this paper, we aim to test and evaluate the current capability of ChatGPT to generate SPARQL queries for retrieval-specific construction workflow information.

3. METHODOLOGY

3.1 Research design

To achieve the identified research objective, the research is designed as shown in Fig.1. We set up an experimental case study of feeding the DiCon ontologies to ChatGPT to test its current capability of generating the SPARQL for retrieval construction information. The results of the experiment are the generated SPARQL queries. To evaluate these queries, we followed Meyer et al. (2023) who selected syntactical correctness, plausible structure, and the coverage of the correct result as three metrics to assess the generated SPARQL queries. First, syntactical correctness aims to check whether the query is following the correct syntax of SPARQL. A query is considered syntactically correct if it can be executed by an SPARQL engine without encountering errors. Second, the plausible structure is used to assess if the query has missing prefixes, wrong use of the classes and properties, or ChatGPT creates the classes and properties out of the given ontologies. The plausible structure is evaluated by manual assessment. Third, the coverage of the correct results is investigated by comparing the query result of the generated SPARQL with the ground truth data.

To evaluate the capability of the ChaptGPT in different scenarios four tests are designed. In the first test, we asked the ChatGPT to create SPARQL queries for direct construction information retrieval. The second test was to ask ChatGPT to generate the SPARQL queries based on different natural language expressions of prompts. In terms of the third test, we asked ChatGPT to generate CONSTRUCT-type SPARQL queries based on updating information based on the given ontology. Finally, we guide ChatGPT to refine the SPARQL queries which are not performing well, to assess the performance of the refinement. Finally, the results of the four tests are assessed based on the previously defined metrics.

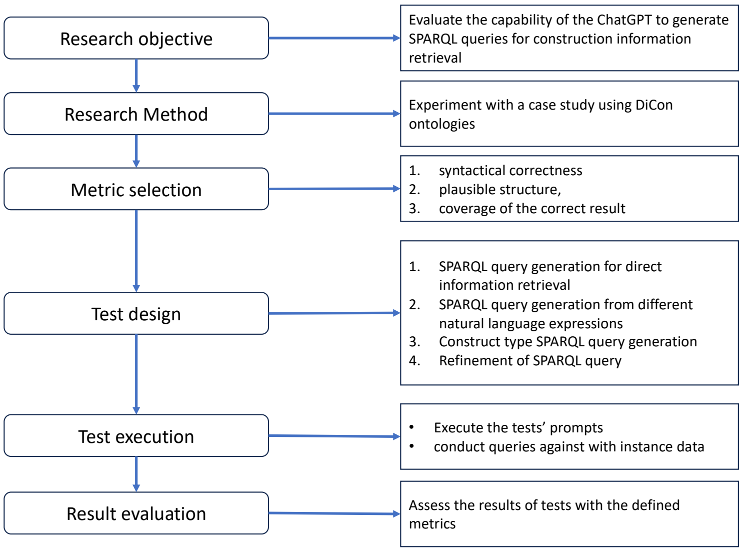

Fig. 1: Research design

3.2 The technical architecture of the experiment

To conduct the above pre-defined tests, we set up a technical architecture of the experiment following the ChatGPT prompt engineering guideline (White et al., 2023) shown in Fig.2. First, due to the large size and high complexity of the original DiCon ontologies, in tests we created a subset of the DiCon ontology contains all essential classes and properties that mapped with the example data graph. Such a process could keep the essence of the ontology but reduce the cost of ChatGPT tokens. ChatGPT 4.0 is the latest model that can directly read textual files (OpenAI, 2023). Thus, we select this version and feed the ontology subset file in Turtle format to ChatGPT 4.0 as the prime prompt. Based on the context feature of the ChatGPT, further SPARQL generation experiments can use the prompt-input ontology subset as the basis of generating the SPARQL queries. Then, the predefined four tests are conducted with the different prompt inputs. The generated SPARQL queries are also used against the instance data stored in GraphDB, a commercial graph store platform by Ontotext (Ontotext, 2023), to retrieve the target information as an evaluation of the syntactical correctness and coverage of the correct result.

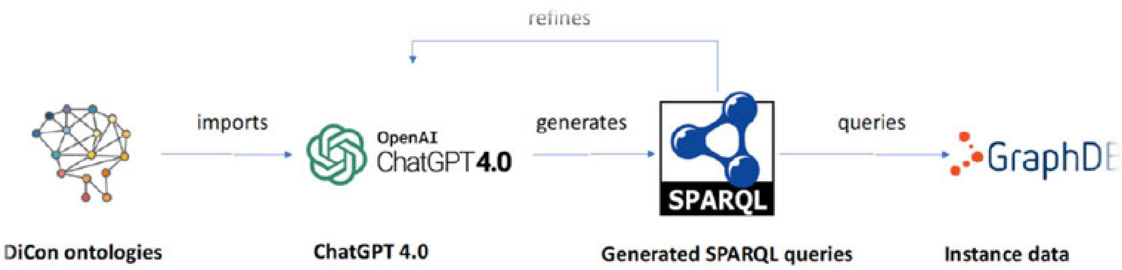

Fig. 2: Technical architecture of the experiment

4. TEST FOR DICON-CHATGPT TO GENERATE SPARQL QUERIES

In this section, a detailed description and result of the aforementioned tests are demonstrated. We also obtained the practical data from previous projects as the ground-truth data to test the SPARQL queries answering.

4.1 Test 1: SPARQL query generation for direct information retrieval

In our first test, we wanted to determine the general capability of ChatGPT to generate SPARQL queries based on the given DiCon ontology subset, to accomplish direct construction information retrieval task. Thus, we asked ChatGPT with Prompts 1.1 and 1.2 to retrieve essential construction information. Both Prompts only utilize terminologies from the DiCon (Zheng et al., 2021).

Prompt 1.1: *Based on the given ontology, create a SPARQL query to find the activity and its related agent and location.*

Prompt 1.2: *Based on the given ontology, create a SPARQL query to find the activity information about its start time and end time.*

Prompt 1.1 aims to retrieve information about construction activity, including its assigned location and agent. This prompt is simple in that in the DiCon class a *dicp:Activity* has direct properties of *dicp:hasLocation* and *dica:hasAgent* towards *dice:Location* and *dica:Agent*. Prompt 1.2 aims to extract the information of the start and end time of the activity. This prompt has an indirect relationship between activities and their start or end times. Because in DiCon, we define the property dicp:occupiesTimeInterval to represent the temporal information of an activity. The range of the *dicp:occupiesTimeInterval* is a *dice:TimeInterval*, which has beginning and end to *dice:TimeInstant* to indicate as the start and end time.

Each of the prompts was asked five times, and the generated results are partially shown in the Appendix due to the length of the paper. In terms of Prompt 1.1, for the five times of the generation, there are four times the ChatGPT uses the correct terminologies in the provided ontology. One time, it was not sure if *dicp: location* was the correct property to use, thus it defined a location property but with the wrong prefix dice: in the query. For Prompt 1.2, ChatGPT generates only one own property to describe the start and end time of an activity. To check the coverage and syntactical correctness of the query, we queried the generated SPARQL to GraphDB with the example data graph. For both of the prompts, all the queries can be successfully executed by the SPARQL engines of GraphDB, which confirms all the queries are syntactically correct. In terms of coverage, all the queries with the correct structure can query the correct answer from the example graph. The metrics results for Prompts 1.1 and 1.2 are listed in Table 1.

Table 1: Metric results of generated SPARQL queries in Test 1.

Prompt	**Metric**	**Result**
1.1	Syntactical correctness	*5/5*
	Coverage of the correct result	*4/5*
	Plausible query structure	*4/5*
1.2	Syntactical correctness	*5/5*
	Coverage of the correct result	*4/5*
	Plausible query structure	*4/5*

4.2 Test 2: SPARQL query generation from different natural language expressions

The second test intends to evaluate the capability of the ChatGPT to generate SPARQL queries based on different natural languages but with the same information retrieval target as Prompt 1.1. This test also analogs the practical nature and scenario that the different end users may have different natural language expressions for the prompts.

Prompt 2.1: *Based on the given ontology, create a SPARQL query that lists the agent and location of an activity*

Prompt 2.2: *Based on the given ontology, create a SPARQL query that lists the worker, workplace of an activity*

In terms of Prompt 2.1, we provided a different expression of Prompt 1.1 but still used the terminologies from the DiCon. In terms of Prompt 2.2, we use similar terminologies that have been mixed usually in the construction domain from describing the classes, to check if the ChatGPT can generate SPARQL with the terminologies out of the ontology. Each of the prompts was asked for five times. For Prompt 2.1, four times it generated the same queries as Prompt 1.1, and one time it used the wrong prefix of the dicp: *location* property. All the queries can be executed in GraphDB, the query with the erroneous prefix returned no location data, while the other four returned correct answers. For Prompt 2.2, only one generated SPARQL was correct to link the term 'worker' to the class agent and the term 'workplace' to the location. ChatGPT created the classes of worker and workplace one time, and the other three times it managed to link the term 'worker' to the class *dica: Agent* but failed to link the term 'workplace' to the class *dice:Location*. All of the generated queries are syntactically correct, but only one query provided us with the correct answer. The metrics results are shown in Table 2.

Table 2: Metric results of generated SPARQL queries in Test 2.

Prompt	**Metric**	**Result**

2.1	Syntactical correctness	*5/5*
	Coverage of the correct result	*4/5*
	Plausible query structure	*4/5*
2.2	Syntactical correctness	*5/5*
	Coverage of the correct result	*1/5*
	Plausible query structure	*1/5*

4.3 Test 3: Infer construction information with SPARQL

SPARQL is not just limited to querying data by using the SELECT statement. It also provides other functionalities such as INSERT, UPDATE, and CONSTRUCT statements to update or create new graph contents (W3C, 2013). Therefore, this test aims to evaluate the capability of ChatGPT to generate a SPARQL query using the CONSTRUCT statement to infer additional construction information by creating a new RDF graph. We provide the Prompt 3 to ChatGPT:

Prompt 3: *Based on the given ontology, create a SPARQL query to construct a new graph, in which if the activity has an agent, construct new triples that the agent "is an agent in" the activity.*

This prompt is based on the predefined ontology that *dica:hasAgent* property has the inversed property of *dica:isAgentIn*, which was not included in the example data graph. This test aims to assess whether ChatGPT can generate CONSTRUCT SPARQL queries that utilize the inversed properties in the ontology to construct new graphs. Similar to the previous tests, Prompt 3 was also asked five times, and we analyzed the syntactic correctness and coverage of the generated queries. The evaluation results for the prompt are listed in Table 3. The metrics results show all the generated queries with plausible query structures, are syntactically correct, and cover the correct result.

Table 3: Metric results of generated SPARQL queries in Test 3.

Prompt	Metric	Result
3	Syntactical correctness	*5/5*
	Coverage of the correct result	*5/5*
	Plausible query structure	*5/5*

4.4 Test 4: Refinement of SPARQL query

In terms of Prompt 2.2, which did not perform well in the test 2. Therefore, in this test, we try to use the contextual feature of the ChatGPT to refine the result by providing more explicit prompts based on the ontology structure. We provide the prompt P4 to the ChatGPT:

Prompt 4: *Refine the previous SPARQL query based on the given ontology, that a "workplace" should link to the class dice:Location.*

Similar to the previous tests, the refinement was also conducted five times, and we analyzed the plausible query structure, syntactic correctness, and coverage of the generated queries. After the refinement, the structure of the query has been significantly improved. All of the queries use the correct terminologies from the provided ontology without misused prefixes, are conductible, and can generate correct answers. The analyzed results for the Prompt 4 are listed in Table 4.

Table 4: Metric results of generated SPARQL queries in Test 4.

Prompt	Metric	Result
4	Syntactical correctness	*5/5*
	Coverage of the correct result	*5/5*
	Plausible query structure	*5/5*

5. DISCUSSION

Corresponding to the above four tests and their results, we assess the current capability of the ChatGPT with three predefined metrics. The overall results of different prompts with three metrics as shown in Fig.3. In the following, we will provide a detailed summary and discussion of the experiment results. First, in terms of syntactical correctness, it is obvious from the experimental results that all the ChatGPT-generated queries in the experiment avoid syntax errors. Such absence of syntactical errors across all generated queries proves ChatGPT comprehends and applies the syntactic rules inherent to SPARQL. This accomplishment is not merely an incidental outcome, but a demonstrable indication of the underlying capabilities that ChatGPT harnesses in generating high-quality, error-free SPARQL queries.

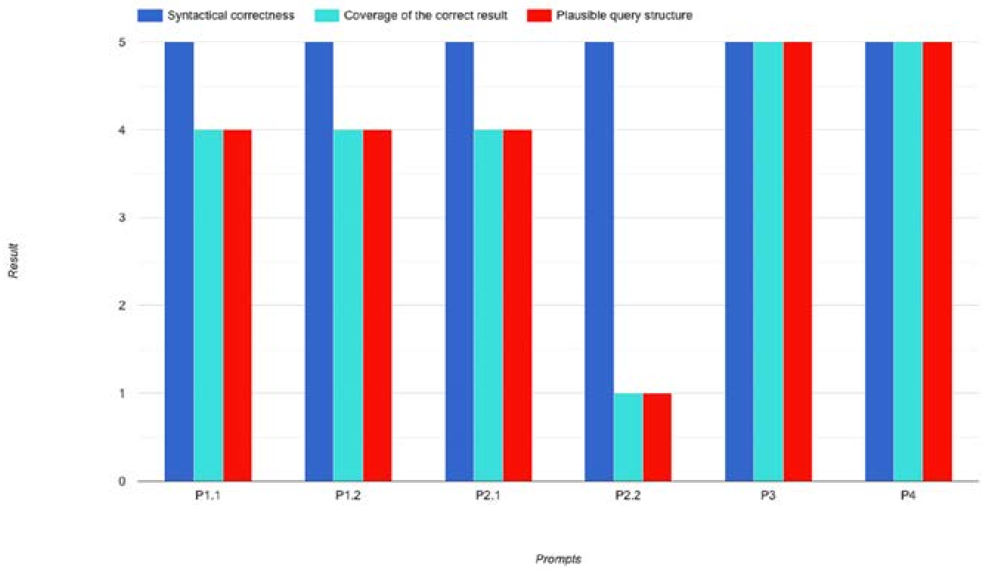

Fig. 3: Overall metrics result of the generated SPARQL for different prompts

Second, when examining the plausible query structure, the detailed analysis revealed that some of the generated results contain structure mistakes. For example, both Prompts 1.1 and 1.2 have one generated query that did not use the correct property in the given ontology but defined a new property as an assumption to complete the query. Although the used terminology is compliant with DiCon, the prefix used was incorrect. For Prompt 2.2, when faced with terminologies outside the ontology, performance had reduced significantly. In this case, it generates only one correct query using the classes and properties defined in the given ontology. The term 'worker' was successfully mapped to the class *dica:Agent*, but the system failed to map 'workplace' to the class *dice:Location* and its associated properties. In test 4, by providing a more explicit mapping instruction prompt to ChatGPT as a refinement, the performance improved. This result reveals that the current ChatGPT still requires explicit prompts using the terminologies defined in the ontology to ensure the generation of plausible queries.

Third, the test results indicate a significant and noteworthy correlation between the structural accuracy of the queries and the subsequent performance of the AI-generated queries in producing accurate query results. In essence, this observation highlights the pivotal role that query structure plays in determining the efficacy of AI-generated queries. Meanwhile, if the generated result is unsatisfactory, ChatGPT can refine the generation by providing new prompts with the correct information to fix the errors.

In summary, the current version of ChatGPT has demonstrated impressive capabilities. It successfully translated natural language questions into syntactically correct SPARQL queries for the DiCon ontology. A detailed analysis revealed some mistakes in the generated results, which can be refined with extra explicit prompts, to elaborate more precise instructions.

6. LIMITATION

This research is just the first research of our research teams to explore the usage of Natural Language Processing (NLP) tools to combine and support semantic construction informatics. Admittedly, this research has the following limitations. First, this research is limited by testing scale. The performance of ChatGPT with entire DiCon ontologies has not been tested and limited numbers of tests have been made. In the future, the test volume and velocity should be enlarged to improve the accuracy of the research. In the future, the full DiCon ontology suite will be also tested with ChatGPT and more comprehensive prompts. Additionally, as DiCon is aligned with other ontologies, such as Building Topology Ontology (BOT), SOSA/SSN, IFCOWL, etc., these ontologies will also be included in the upcoming more complex tests. Second, this research is only tested using ChatGPT. Currently, ChatGPT is the most used NLP tool and is easy to deploy and test. Although ChatGPT is under continuous updating, as a commercial solution, its closed source and black-box nature makes it difficult to optimize and train. Therefore, besides the ChatGPT, in future research, other LLM models and NLP tools should be also tested and explored, for example, the Falcon LLM (Technology Innovation Institute, 2023). More construction domain-specified training based on the open-sourced LLM will also be conducted. Third, the prompts themselves would affect the generated query results. Throughout this research, the prompts provided to ChatGPT have been intentionally kept simple and straightforward to gauge ChatGPT's performance in generating SPARQL queries. However, recognizing the multifaceted nature of semantic querying and the potential intricacies within construction information, future studies will necessitate a broader spectrum of test cases with more specific construction information retrieval tasks. By incorporating more intricate prompts, further research will better evaluate ChatGPT's capacity to handle complex query generation tasks in the construction domain. Another research track is also studying the prompt development manner based on the readability score.

7. CONCLUSION

This paper tested the capability of ChatGPT to generate SPARQL queries with a case study based on the DiCon ontologies for construction workflow information retrieval. We designed and conducted a set of tests to assess the current capability of ChatGPT to generate the SPARQL query for solving the construction domain-specific task of information retrieval.

Overall, as observed from the result, ChatGPT has demonstrated its impressive capability of generating SPARQL queries for the given ontology to retrieve target information on the construction domain level. The experiments show that ChatGPT can avoid syntax errors, and read and utilize the given ontologies as the basis of SPARQL generation. However, the execution of the test process and evolution of the generation result also reveal several current limitations of ChatGPT in generating SPARQL queries. For example, ChatGPT cannot fully understand the given ontology, and the quality of the generated SPARQL queries highly relies on the explicitness of the given prompts.

In future research, we would also continue the exploration of using LLM solutions, including ChatGPT and other tools, to combine with the Semantic Web implementation in the construction domain. One future research topic is to illustrate the construction information, from SPARQL queries generated by Chat-GPT on Extended Reality devices. Simultaneously, we would also test the feasibility of ChatGPT to create RDF converters, which will convert tabular data into RDF format mapped with the DiCon ontology.

ACKNOWLEDGMENTS

Partial of the researchers received financial support from the ACTOR project. ACTOR is supported by Business Finland's Low Carbon Built Environment Program and receives funding from the EU's Recovery and Resilience Facility (from 2022-). The authors are grateful for the study’s financial and data support.

APPENDIX: Prompts and Example ChatGPT SPARQL results

Prompts	Example result

Prompt 1.1: *Based on the given ontology, create a SPARQL query to find the activity and its related agent and location.*	PREFIX dicp: <https://w3id.org/digitalconstruction/0.5/Processes#>
	PREFIX dica: <https://w3id.org/digitalconstruction/0.5/Agents#>
	PREFIX dice: <https://w3id.org/digitalconstruction/0.5/Entities#>
	SELECT ?activity ?agent ?location
	WHERE {
	?activity rdf:type dicp:Activity .
	?activity dica:hasAgent ?agent .
	?activity dice:hasLocation ?location .
	}

Prompt 1.2: *Based on the given ontology, create a SPARQL query to find the activity information about its start time and end time.*	PREFIX dicp: <https://w3id.org/digitalconstruction/0.5/Processes#> PREFIX dice: <https://w3id.org/digitalconstruction/0.5/Entities#> SELECT ?activity ?startTimeInstant ?endTimeInstant WHERE {

	?activity rdf:type dicp:Activity . ?activity dicp:occupiesTimeInterval ?timeInterval . ?timeInterval dice:hasStart ?startTimeInstant . ?timeInterval dice:hasEnd ?endTimeInstant . }

Prompt 2.1: *Based on the given ontology, create a SPARQL query that lists the agent and location of an activity*	PREFIX dicp: <https://w3id.org/digitalconstruction/0.5/Processes#>
	PREFIX dica: <https://w3id.org/digitalconstruction/0.5/Agents#>
	PREFIX dice: <https://w3id.org/digitalconstruction/0.5/Entities#>
	SELECT ?activity ?agent ?location
	WHERE {
	?activity rdf:type dicp:Activity .
	?activity dica:hasAgent ?agent .
	?activity dice:hasLocation ?location .
	}

Prompt 2.2: *Based on the given ontology, create a SPARQL query that lists the worker, workplace of an activity*	PREFIX dicp: <https://w3id.org/digitalconstruction/0.5/Processes#>
	PREFIX dica: <https://w3id.org/digitalconstruction/0.5/Agents#>
	PREFIX dice: <https://w3id.org/digitalconstruction/0.5/Entities#>
	SELECT ?activity ?worker ?workplace
	WHERE {
	?activity rdf:type dicp:Activity .
	?activity dica:hasAgent ?worker .
	?activity dice:hasLocation ?workplace .
	?worker rdf:type dica:Worker . # Assuming "Worker" is a subclass or type of Agent
	}

Prompt 3: *Based on the given ontology, create a SPARQL query to construct a new graph, in which if the activity has an agent, construct new triples that the agent "is an agent in" the activity.*	PREFIX dicp: <https://w3id.org/digitalconstruction/0.5/Processes#>
	PREFIX dica: <https://w3id.org/digitalconstruction/0.5/Agents#>
	CONSTRUCT {
	?agent dica:isAgentIn ?activity .
	}
	WHERE {
	?activity dicp:hasAgent ?agent .
	}

Prompt 4: *Refine the previous SPARQL query based on the given ontology, that a “workplace” should link to the class dice:Location.*	PREFIX dicp: <https://w3id.org/digitalconstruction/0.5/Processes#>
	PREFIX dica: <https://w3id.org/digitalconstruction/0.5/Agents#>
	PREFIX dice: <https://w3id.org/digitalconstruction/0.5/Entities#>
	SELECT ?activity ?agent ?location
	WHERE {
	?activity rdf:type dicp:Activity .
	?activity dica:hasAgent ?agent .
	?activity dice:hasLocation ?location .
	}

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EXTRACTING INFORMATION FROM CONSTRUCTION SAFETY REQUIREMENTS USING LARGE LANGUAGE MODEL

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ABSTRACT: *The construction industry has long been recognized for its complex safety regulations, which are essential to ensure the well-being of on-site employees. However, navigating these regulations and ensuring compliance can be challenging due to the volume and complexity of the documents involved. This study proposes a novel approach to extracting information from construction safety documents utilizing Large Language Models (LLM), called CSQA, to provide real-time, precise answers to queries related to safety regulations. The approach comprises three modules: (1) the construction safety investigation module (CSI) collects safety regulations for building the information needed. By leveraging a collection of safety regulation PDFs, the system follows a process of text extraction, preprocessing, and global indexing for efficient search. (2) The safety condition identification module (SCI) retrieves the CSI database; after that, the LLM, with its extensive training, processes user queries, searches the indexed regulations, and retrieves pertinent information. (3) the safety information delivery (SID) would provide the answer to the user and incorporate a feedback mechanism to further refine system accuracy based on user responses. Preliminary evaluations reveal the system's superior performance over traditional search engines, owing to its ability to grasp query context and nuances. The CSQA presents a promising method for accessing safety regulations, with potential benefits including reduced non-compliance incidents, enhanced worker safety, and streamlined regulatory consultations in construction.*

KEYWORDS: *Construction safety document, extraction, LLM.*

1. INTRODUCTION

Safety has consistently been seen as a vital concern within the construction industry. Workplace safety catastrophies can result in major loss of life and damage to property with severe repercussions (S. V.-T. Tran et al., 2023; S. V. T. Tran et al., 2021). According to the latest statistics from the Occupational Safety and Health Administration (*OSHA Fatality Report*, n.d.), the construction industry witnessed an annual total of 1,008 fatalities in 2020. Notably, falls from elevated positions constituted around thirty-three percent of these. According to data from Statistics Korea (*Construction Work | Statistics Korea*, n.d.), the construction business in South Korea accounted for more than 50% of all fatal accidents within the industry. To prevent accidents at construction sites, several scholars and professionals have demonstrated that implementing enhanced safety measures in the workplace might reduce and prevent accidents (Bao et al., 2022; S. V. Tran et al., 2022; S. V. T. Tran et al., 2022). Therein, field compliance checking is a crucial endeavor to identify non-compliance with construction safety standards, with the primary objective of safeguarding employees against potential safety events (Jeong et al., 2023; Kang et al., 2023).

Analyzing construction safety documents with natural language processing (NLP) techniques enables automatic information extraction of safety requirements. For instance, Feng and Chen (Feng & Chen, 2021) proposed a framework based on deep learning to extract event-related information (e.g., date, location, and type of accident) from accident news reports for construction safety management. Rupasinghe and Panuwatwanich (Rupasinghe & Panuwatwanich, 2021) proposed a rule-based technique for extracting information about hazards from accident reports. Baker et al. (Baker et al., 2020) suggested employing NLP (a collection of text patterns) to uncover injury precursors. These works together focused on either the study of injury and accident records or the extraction of hazard variables. Despite these studies, there is a dearth of research aimed at automatically extracting requirements from construction safety rules in order to enable field compliance. Besides, the information extraction should provide users with precise and timely responses to their inquiries within human natural language.

Large Language Models (LLM) have emerged as a game-changing technology, displaying extraordinary ability in natural language processing jobs. Incorporating LLMs into construction safety provides a distinct benefit in its capacity to customize to particular, project-centric data. This is especially important given the vast volumes of

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Si Tran, Nasrullah Khan, Emmanuel Charles Kimito, Akeem Pedro, Mehrtash Sotani, Rahat Hussain, Taehan Yoo, Chansik Park, *Extracting Information from Construction Safety Requirements Using Large Language Model*, pp. 761-767, DOI 10.36253/979-12-215-0289-3.76

private paperwork that projects often require. Every project in the construction environment is unique, with its own blueprints, safety regulations, and vendor-specific rules, often encased inside PDFs and other digital forms. LLMs have the capacity to be trained or fine-tuned on project-specific datasets. Once a company uploads its confidential documents, the LLM can absorb this data, guaranteeing that when queries are posed, the solutions are general and suited to the context of that specific project's data.

This research proposes CSQA approach, a unique method for extracting construction safety documentation using Large Language Models (LLM), to answer real-time safety regulatory questions and fill the knowledge gap for industry experts. The method has three parts: (1) The construction safety investigation module (CSI) gathers building safety rules. The system uses safety regulation PDFs for text extraction, preprocessing, and global indexing for efficient search. (2) The safety condition identification module (SCI) obtains the CSI database, then the LLM analyzes user queries, examines the indexed rules, and retrieves relevant information with its thorough training. (3) Safety information delivery (SID) would address the user and offer feedback to improve system accuracy depending on user replies. Section 2 discusses the current state of construction safety information retrieval and LLM. Section 3 will present the recommended approach. The authors produce case scenarios in Section 4 to validate the approach. Subsequently, the discussion and conclusions of the study are presented.

2. LITERATURE REVIEW

2.1 Current state of construction safety information retrieval and extraction

Over the years, the construction industry, renowned for its complex projects and the resulting safety imperatives, has accrued a vast repository of safety regulations, guidelines, and best practices. Traditionally, retrieving and extracting relevant safety information was primarily a manual process (Zhong et al., 2020). Professionals frequently find themselves navigating through extensive physical binders or digital documents. This approach, while exhaustive, is fraught with difficulties. Due to the time-consuming nature of manual searches and the possibility of human error, there are frequent voids in the incorporation of vital safety directives(S. V. T. Tran et al., 2021). Moreover, the dynamic nature of construction projects, with their distinct challenges and parameters, necessitates a customized understanding of safety regulations, which manual searches cannot provide efficiently(Wu et al., 2022).

Efforts have been made since the advent of the digital age to expedite this procedure (S. V. T. Tran et al., 2021). Initially, safety information was migrated to digital databases, enabling keyword-based searches. Even though this change facilitated the retrieval process to some degree, it was not without limitations. Keyword searches frequently return many results, necessitating additional sorting to locate relevant information. The lack of contextual comprehension and the static nature of these databases provided a wealth of information without the nuanced interpretation required for specific project scenarios. For instance, Feng and Chen (Feng & Chen, 2021) proposed a framework based on deep learning to extract event-related information (e.g., date, location, and type of accident) from accident news reports for construction safety management. Rupasinghe and Panuwatwanich (Rupasinghe & Panuwatwanich, 2021) proposed a rule-based technique for extracting information about hazards from accident reports. Baker et al. (Baker et al., 2020) suggested employing NLP (a collection of text patterns) to uncover injury precursors. This context paves the way for investigating more sophisticated AI-driven methodologies capable of efficient information retrieval and contextual comprehension and understanding.

2.2 Information extraction using Large Language Model

Natural language processing allows a computer to interpret and process natural language text similarly to a person. Information extraction (IE) is a branch of natural language processing that obtains needed information from text sources. In general, there are two techniques for information extraction [11]: (1) machine learning (ML) and (2) rule-based approaches. However, research has focused on using rule-based techniques because training samples are few. Large Language Models (LLM) have transformed natural language processing, providing a game-changing answer to this problem.

Within the realm of construction, safety stands as a paramount pillar, with documentation and guidelines serving as the backbone to ensure the welfare of all stakeholders. Extracting relevant, actionable information has been a persistent challenge with the sheer volume and complexity of safety documentation. The potency of LLMs in safety information extraction lies in their ability to discern the context of a query and retrieve information that is not just relevant but also actionable. For instance, when asked about safety protocols for handling specific machinery, an LLM can sift through a vast repository of safety guidelines, pinpointing the exact procedures, precautions, and best practices.

Besides, construction safety may benefit from Large Language Models (LLMs) since they can be tailored to project-specific data, particularly given the vast volumes of private paperwork projects frequently include. Every construction project has plans, safety regulations, and vendor-specific rules, frequently in PDFs. LLMs may be trained or fine-tuned using project-specific datasets. The LLM may integrate confidential materials uploaded by a company to provide project-specific solutions to inquiries. Project secrecy and relevance are greatly affected by LLMs' project-specific customization. Traditional search engines and databases may provide general results or need substantial human labeling to identify project-specific data. LLMs automatically comprehend the context after being fine-tuned on a project's papers, ensuring that every answer meets the project's particular characteristics and criteria. This improves information retrieval accuracy and relevance and keeps sensitive project data in that context, protecting private project information.

3. METHOD

The primary purpose of developing an approach of extracting construction safety requirements using large language model. The structure and key features of the system are shown in **Figure 1**, which comprises three modules. (1) The construction safety investigation module (CSI) gathers building safety rules. The system uses safety regulation PDFs for text extraction, preprocessing, and global indexing for efficient search. (2) The safety condition identification module (SCI) obtains the CSI database, then the LLM processes user queries, examines the indexed rules, and retrieves relevant information with its thorough training. (3) Safety information delivery (SID) would address the user and offer feedback to improve system accuracy depending on user replies.

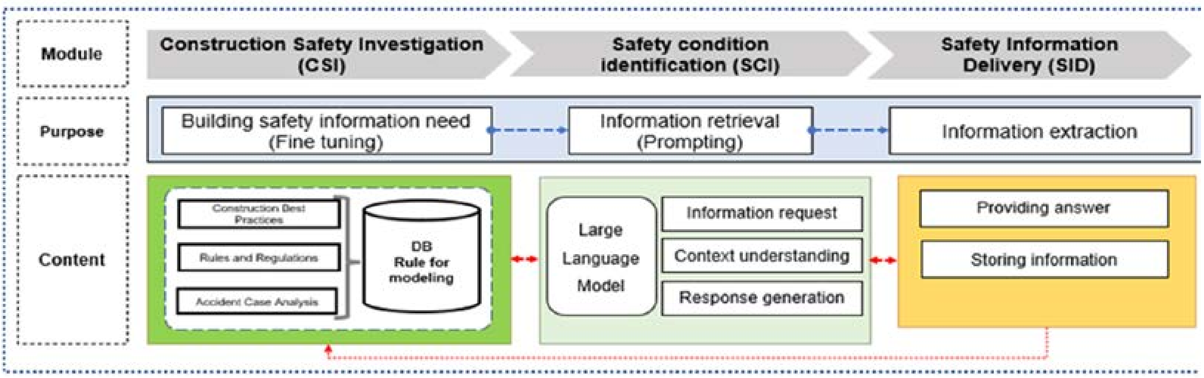

Fig. 1: Proposed approach of Extracting Construction Safety Requirements using Large Language Model

The Construction Safety Investigation (CSI) module is the foundational block in this approach, concentrating on the meticulous collection of safety regulations essential for creating the requisite information database. This module predominantly handles a variety of PDF safety regulation documents and serves as the entry point for raw safety data. The CSI module has multiple functions, including text extraction, preprocessing, and global indexing. Text extraction is crucial, as it converts the information in PDFs into a structured format. Preprocessing then entails cleaning and normalizing the extracted text to prepare it for the subsequent phases.

The Safety Condition Identification (SCI) module serves as the interface between the foundational database created by the CSI module and the user-facing delivery module in this approach. The primary responsibility of the SCI module is to interact with the CSI database and retrieve pertinent safety information based on user queries. The Large Language Model (LLM) incorporated into this module plays a crucial role, utilizing its extensive training to process and comprehend user queries in real time. The LLM examines the indexed regulations in the CSI database and retrieves relevant information, considering the context and subtleties of the user's query. Incorporating LLM into this module ensures that the retrieval process is accurate, context-aware, and efficient, providing instantaneous responses to user queries.

This approach also includes the Safety Information Delivery (SID) module, which focuses on delivering the retrieved and processed safety information to the end-user. It serves as the user interface, providing plain, concise, and pertinent responses to user queries. Beyond merely delivering information, the SID module includes a feedback mechanism that allows users to rate the accuracy and relevance of the provided answers. This user feedback is crucial for refining the system's precision and improving dependability. By perpetually incorporating user feedback, the SID module ensures that the system evolves and adapts to the users' changing requirements and preferences, maintaining its relevance and effectiveness in delivering precise construction safety information.

3.1 Prototype development

Figure 2 depicts prototype development process and tool uses for the proposed approach. The authors used Langchain, an open-source Python library for building LLM-powered applications. Utilizing LLMs with vector indexing via embedding provides a foundation for the solution. Initially, a comprehensive safety regulation database is accessed and processed to collate information predominantly housed in PDF formats. Subsequently, this information is extracted, followed by a data cleaning procedure to omit redundant elements, such as punctuation, commas, and line spaces. For this operation, a smaller LLM from the Spacy library is deployed. The information is segmented into manageable chunks to facilitate efficient filtering, aligned with the embedding model's chunk size within the embedding space. After the initial processes, the refined information is fed into a text embedding model to formulate and archive the information in a vector database, commonly referred to as a vector store, pivotal for advanced information retrieval mechanisms. The essence of the embedding model is to transmute high-dimensional textual data into a more condensed representation, aligning with the operational frameworks of LLMs, as we can't put our whole PDF textual information in user query or Prompt. For this critical transformation, the OpenAI text embedding model is employed. The formulated vector database harboring safety regulation information is then integrated into the pipeline, allowing LLMs to perform advanced retrieval of information pertinent to user queries.

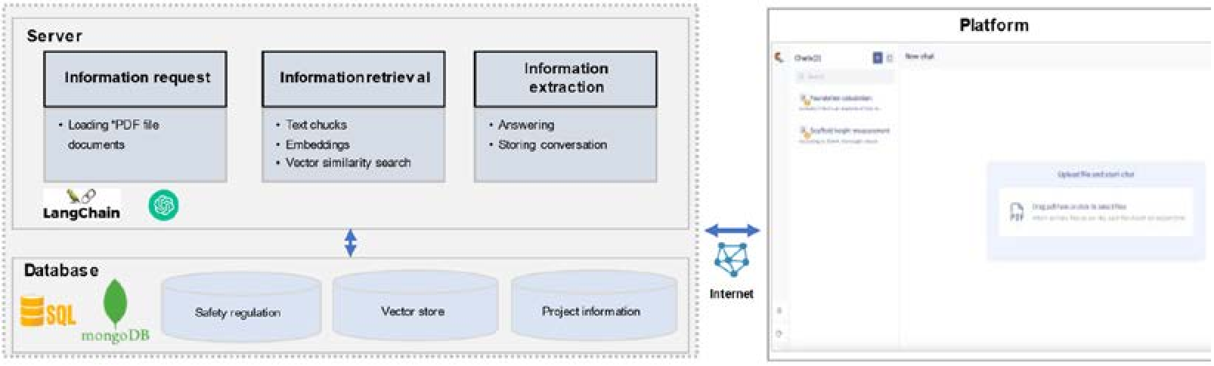

Fig. 2: System architecture

The creation of the vector store is facilitated using FAISS for efficient similarity search and clustering analysis of high-dimensional vector databases. Upon establishing the vector database, it is intricately interwoven within the operational pipeline, enabling LLMs to execute sophisticated information retrieval and interaction, utilizing OpenAI's GPT-4 through Langchain, a versatile open-source framework for building AI apps and Chatbots. The streamlined process integrates FAISS, user queries, and LLMs responses in a seamless flow. When a user initiates a question, it is directed to FAISS's sophisticated similarity search algorithm, which extracts relevant information from the vector database used by LLMs in embedding form.

4. CASE STUDY

The authors performed a case study of safety information extraction related to scaffolding during construction by implementing the CSQA approach, as illustrated in Figure 3. The extraction of safety regulations, specifically OSHA 1926 Subpart L, is pivotal in maintaining a high level of safety in construction environments where scaffolding is utilized. To do this, the authors download A Guide to Scaffold Use in the Construction Industry as a PDF file and then upload it to the CSQA prototype system. After that, the safety managers query the information related to their needs. By meticulously extracting and implementing each safety provision laid out by OSHA, construction companies can significantly mitigate the risk of scaffold-related incidents, protecting workers from falls, structural collapses, and falling objects. This process of extracting and adhering to OSHA's stringent safety regulations is essential in fostering a culture of safety within the construction industry, emphasizing the importance of the well-being of every individual on the construction site and ensuring the successful and safe completion of construction projects.

Fig. 3: The construction jobsite using both fixed and mobile scaffolding

In the case study, both fixed and mobile scaffolding were used at the construction jobsite (as illustrated in Fig. 3). To prepare for the safety inspection process, the safety manager considers some potential hazards situation that may occur during using scaffolding system. The results of the prompting process were illustrated in Fig. 4. In the scenario, the safety manager would request information about the maximum number workers allowed to use the scaffolding simultaneously. After prompting, the results of extractions were described in Fig. 4.

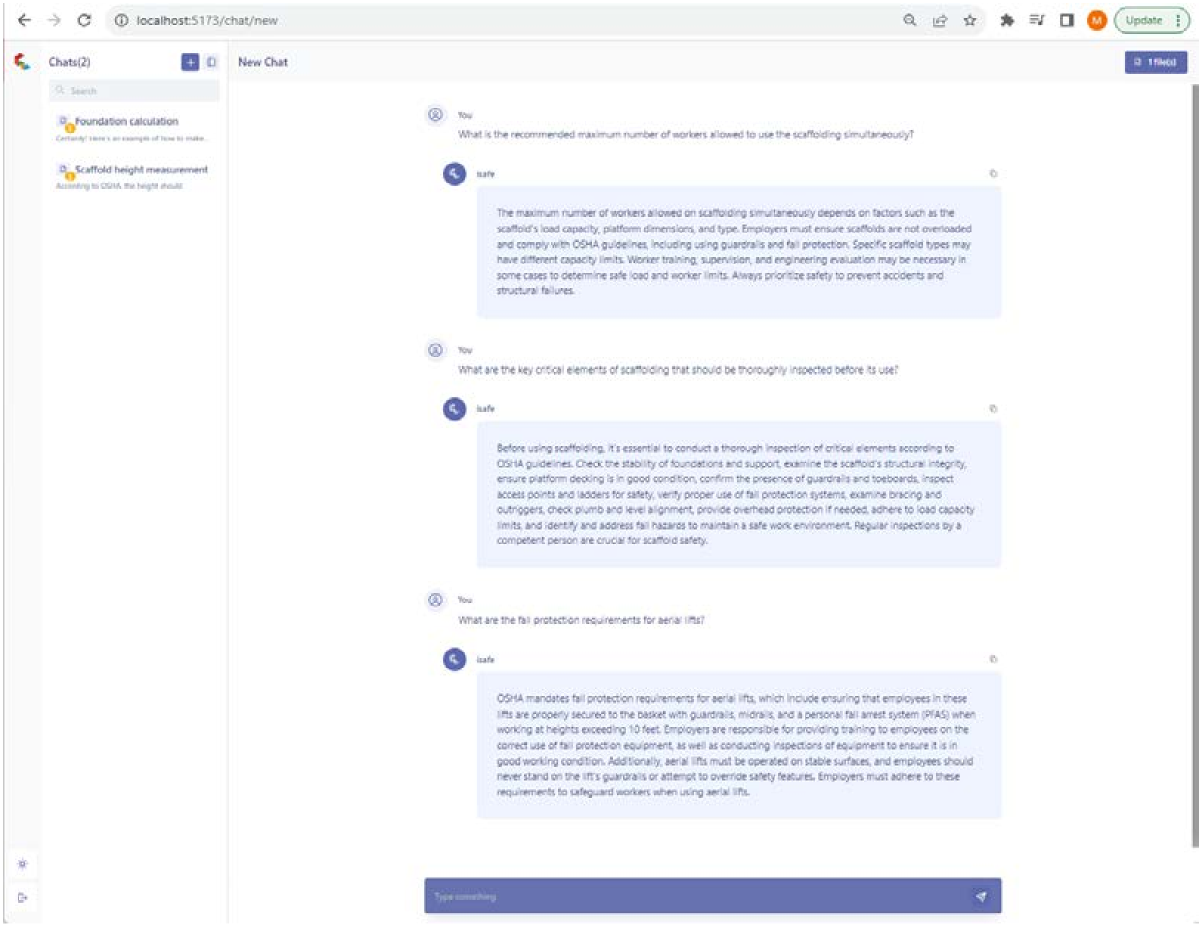

Fig. 4:The results of safety information extraction

5. DISCUSSION AND CONCLUSION

The study aimed to improve construction safety by proposing an approach to extracting safety requirements using a large language model. A thorough literature review highlighted the significance of safety information retrieval and extraction. Accordingly, the safety requirements were collected and tailored for building the database, which is contained in the safety investigation module (CSI). The system uses safety regulation PDFs for text extraction, preprocessing, and global indexing for efficient search. The safety condition identification module (SCI) obtains the CSI database, then the LLM processes user queries, examines the indexed rules, and retrieves relevant information with its thorough training. Safety information delivery (SID) would address the user and offer feedback to improve system accuracy depending on user replies. Hence, the safety requirements could be extracted following the request of site employees. The authors developed the prototype of an LLM-powered application by using Langchain to validate the approach. The results show that the maximum number of workers allowed to use the scaffolding simultaneously was retrieved from the guide to scaffold use in the construction industry.

However, the research has the following limitations: (1) The study concentrates on optimizing a database of safety requirement information; however, it does not discuss the algorithm's architecture and precision. (2) The case study is only used to extract scaffolding-related information. For future studies, the authors will analyze additional accident reports and regulations to develop potential hazard situations associated with a specific activity. Additionally, the authors will concentrate on developing a system based on the proposed method. Then, we examine the effectiveness of the system with larger initiatives and more project members.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government(MSIT) (No. NRF-2022R1A2B5B02002553). This research was conducted with the support of the "National R&D Project for Smart Construction Technology (No.23SMIP-A158708-04)" funded by the Korea Agency for Infrastructure Technology Advancement under the Ministry of Land, Infrastructure and Transport, and managed by the Korea Expressway Corporation.

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MODELLING AND MANAGING BUILT HERITAGE KNOWLEDGE: AN ONTOLOGY-BASED APPROACH FOR MULTI-LAYERED ARCHAEOLOGIES AND HISTORICAL PRODUCTION PROCESS REPRESENTATION

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ABSTRACT: *Classical and industrial archaeologies are a complex cultural field where singularity and uniqueness are expressed through past memory evidence and identity recognition. In order to obtain these values acknowledgement, it is compelling to highlight the material and intangible knowledge by using suitable ICT tools capable of handling complexity and managing large sets of heterogeneous data usually subjected to changes, different interpretations, inconsistencies and sometimes uncertainty. Although the HBIM method has been largely used in the past years, it shows significant limits when dealing with large and heterogeneous information requiring the introduction of advanced methods and tools. In this context, this study presents an approach to the architectural heritage and historical manufacturing activity representation based on integrating the HBIM process with a structured knowledge base, demonstrated through its application to the Sanctuary of Hercules and the former Segrè Papermill case study. The work develops an ontology-based system using existing ontologies for the three domains of interest: architectural artefact, cultural heritage and industrial processes directly connected with the informative model. The intent is to give an overall support system for the complex semantics formalization of these assets to aid the interpretation, intervention and valorization activities.*

KEYWORDS: *Archaeology, Industrial heritage, Knowledge representation, HBIM, Ontologies, Linked data*

1. INTRODUCTION

The widespread of various digital approaches in the built heritage field has raised multiple issues related to the effectiveness of those different methodologies. In this context, it is compelling to comprehend the complex nature of the these specific sites and to define reliable methods to document research and investigation processes for the recovery, intervention and valorization activities. Particular assets distinguished by multiple archaeological stratifications are emblematic cases that perfectly outline the critical aspects of current practices. The knowledge representation and management activities play a crucial role alongside the historical and archival research, the integrated survey and the information modelling of these artefacts, to address the challenges of complex heritage assets related to their uniqueness and singularity/rarity and to solve critical issues of interoperability, alignment of cataloguing systems, in order to make knowledge shareable among the various actors involved in decision-making processes.

Within such peculiar applications, this study tries to apply effective digital knowledge technologies to address the main research question, or rather the knowledge representation in a complex evolutionary scenarios, such as multiple archaeological sites, by integrating information modelling (BIM) and semantic web technologies (ontologies). In particular, with a specific focus on modelling the Segrè papermill historical industrial process, linked to the architectural artefact and its historical evolution. The aim is to highlight comprehensively the industrial archaeology aspects which is defined as an interdisciplinary study field related to both the historical issues of the industry's world and the material culture (processes, machines, workers life). In fact, the industrial archaeology represents a combined form of technological and humanistic culture, whose value extends and matures overtime. Therefore, the experiment focuses on covering the gap in digital data documentation of industrial archaeology and historical manufacturing processes to represent multidisciplinary concepts correlations in a machine-readable way. Furthermore, the study proposes an approach to the knowledge representation and global management for the investigation process of this unique heritage field.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Cassia De Lian Cui, Antonio Fioravanti, Edoardo Currà, Davide Simeone, Stefano Cursi, *Modelling and Managing Built Heritage Knowledge: An Ontology-Based Approach for Multi-Layered Archaeologies and Historical Production Process Representation,* pp. 768-780, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.77

1.1 Current digital documentation and investigation processes for built heritage

Over the past decade, we have observed a growing focus on Building Information Modeling in the area of heritage architecture also, referred to as Heritage (or Historical) BIM / HBIM. Currently, the most established HBIM workflow consists of surveying the building by point cloud used as a reference to reconstruct simplified geometries employing BIM objects, which are assigned attributes and linked documents, boards and databases helpful in enriching the model with information produced and used by specialists in the field (Logothetis et al., 2015; López et al., 2018; Pocobelli et al., 2018).

If, in the case of the design of new buildings, the definition of accurate and complete documentation of what is to be built goes hand in hand with the progressiveness of the definition of the project itself, and is, therefore, fully consistent with the information practices imposed by BIM environments, in the case of the processes that characterize the activities of investigation and restitution of an existing asset the knowledge we have of the latter, in addition to coming from extremely heterogeneous sources, is subject to continuous changes, interpretations, uncertainties and gaps that must be able to persist until the end of the process and beyond (Bianchini, 2014). In fact, information management in this field is still mainly based on a documentary approach (Moscati, 2021) in which information is stored by presenting it in a linear and orderly manner but in a flat and static form that does not allow the possibility of movement and connection between the information itself. The need to overcome these limitations led to the research of new systems that could allow machines to automatically combine knowledge from different sources and, even better, derive new knowledge from them.

Following linked data principles, ontologies are languages used by semantic web resources to represent knowledge and concepts within a specific domain (Gruber, 1993). In the case of cultural heritage and more in detail built heritage fields, ontologies have been developed to organize and structure information related to buildings, historical monuments, archaeological sites, and other forms of architectural heritage. These ontologies enable better management, search, sharing, and data interoperability in the built heritage field.

The direction in which major international research infrastructures are moving (DARIAH, Etc.) seeks to transform the 'Web of documents' into a 'Web of data', consisting of concrete 'objects' that machines can process (machine understandable). The aim is to provide computers with the ability to combine data to create new knowledge, form new connections and draw new conclusions from indexed data, automating what has hitherto been the exclusive preserve of humans and minimizing the separation between discovery (locating bibliographic news) and delivery (finding the document) so that an ecosystem of metadata can be created. This operation will soon allow global data availability within a larger framework of openness and interconnection of information, enhancing the effectiveness and visibility of information available online.

1.2 Existing ontologies for industrial processes representation

Significant efforts exist to standardize ontologies across industries. Organizations such as Industrial Ontologies Foundry (IOF) (Drobnjakovic et al., 2022) and Manufacturing Enterprise Solutions Association (MESA) (Kazil et al., 2020) are collaborating to develop common ontologies and data models to improve interoperability among manufacturing systems. To date, the mid-level manufacturing ontologies available are the Manufacturing Semantics Ontology (MASON) (Lemaignan et al., 2006) and the Manufacturing Reference ontology (MRO) (Usman et al., 2013). However, they are only able to represent the production and design part of the manufacturing domain (Sanfilippo et al., 2021) and have limited mutual interoperability (Francesconi et al., 2010).

The Supply Chain Reference Ontology (SCRO) (Ameri et al., 2020) is a pilot ontology that extends BFO and IOF Core able to provide the basic ontological constructs needed to represent a supply chain in terms of structure (members and their roles, functions, capabilities, relations, and resources) and operations (processes and flow of material and information). Similarly, the Supply Chain ONTology (SCONTO) (Vegetti et al., 2016) formally describes a supply chain at various abstraction levels. Resources such as workstations, machines, tools and fixtures are formally represented in the Manufacturing Service Description Ontology (MSDL) (Ameri & Dutta, 2006).

Furthermore, with the advent of the fourth industrial revolution (Industry 4.0) and the expansion of the Internet of Things (IoT) into the industrial sphere, ontologies become even more important for organizing and understanding data from an increasing number of connected devices and intelligent systems (Sampath Kumar et al., 2019). Industry 4.0 is mainly based on robotic agents that are responsible for performing the main operations in a smart manufacturing environment. The standardization of the knowledge representation is based on standard ontologies, which are the CORA Ontology for robotics and automation (Prestes et al., 2014) and ROA Ontology (Cheng et al., 2016) that defines the main notions of behavior, function, and goal. Focusing specifically on the manufacturing resources, in literature we can find a variety of standard and ontologies that understand resources differently. Based on industrial standard, resources are defined as " any device, tool and means, except raw material and final product components, at the disposal of the enterprise to produce good and services" (ISO 15531-1; ISO, 2004a). "The types of resources involved in the manufacturing operational management are: personnel, material, equipment" (IEC 62264; IEC, 2013); "Means used by an activity to transform input into output" (ISO 20534; ISO, 2018). As we can see the terminology relies on not aligned vocabularies and we can define three different approaches that have distinct views on manufacturing resources. The first one relates the manufacturing activities occurrences with the resources model (Sarkar & Šormaz, 2019), the second one connects the resource to the activities primarily (Sanfilippo, 2018), the last one presents the resources directly related to the agents goals (Sanfilippo, 2018). The user case needs should rely on adopting one or the other. Furthermore, as we can see in the literature, many studies and approaches exist for contemporary manufacturing processes and Industry 4.0. At the same time, it lakes in the representation of historical industrial processes, therefore in the ontology reuse process, we adapted existing classes, relations and proprieties to our specific use case.

1.3 Existing ontologies for cultural heritage representation

Several knowledge structures have been developed to represent and manage cultural heritage data (Doerr et al., 2020; Hellmund et al., 2018). For instance, the Getty Foundation developed a SPARQL version of its thesaurus (Harpring, 2010). In addition to those mentioned above, one of the most widely used conceptual models to describe cultural heritage in general with extensions possibility to fit built heritage is the CIDOC Conceptual Reference Model (CIDOC-CRM) (Martin Doerr, 2003). CIDOC-CRM provides a conceptual model to describe cultural heritage in general but can be broadened to fit built heritage aspects.

Extensions of CIDOC-CRM include the CRMba model (Ronzino, 2015) conceived to support the archaeological documentation of buildings with an emphasis on recording stratigraphic units and the evolution of the structure over time. Furthermore, other specific ontologies have been developed to address specific issues in built heritage, such as conservation, documentation, and management. For example, Acierno et al. (2017) extend the domains of CIDOC with an ontological structure that covers aspects concerning both the typological and the constructive entities of historic buildings, and the documentation and investigation activities conducted by specialists for the artefact study and preservation. Colucci et. al. (2021) deal with the formal conceptualization to represent the built and architecture domain by proposing an ontological scheme that focuses on connecting semantic and geometric information to generate a parametric and structured model from point clouds.

In a broader context, not confined exclusively to the ontologies field, initiatives such as the EUROPEANA (Europeana, 2017) and ARCHES (Myers et al., 2016) projects aim to create open digital infrastructure to enhance the semantic representation of data related to built heritage. It is clear that the development of ontologies for built heritage is an active field of research and development. New ontologies and approaches continue to be proposed and developed, especially to integrate ontological approaches with 3D and HBIM models (Cursi et al., 2022) to improve the representation and interoperability of information related to this domain.

1.4 Digital approaches for classical and industrial archaeologies

In the archaeological field, the structures and the architectural elements are usually partially visible, restored or modified, often with missing parts and multiple transformations during time. Digital representation is a big challenge since the archaeological reports on the excavations and related documentation are usually the only available data. The models tested in this field primarily deal with virtual reconstruction, starting from different survey techniques to immersive and virtual fruition. Most of the case studies considered are as-built BIM to represent the actual state of the remains with a BIM semantic structures through manual operations or automatic segmentation algorithms (Achille et al., 2015; Bosco et al., 2019; Di & Wu, 2011; Guerrero Vega & Pizzo, 2021; Moyano et al., 2021; Scianna et al., 2021; Trizio et al., 2018). In Garagnani's work (2016), they defined a process of information cataloguing ArchaeoBIM as useful for documentation and consultation and for analytical studies to accompany the reconstruction activity. The main focus of some of them is on the stratigraphic analysis in the HBIM workflows (Diara & Rinaudo, 2020) and the development of the HBIM cloud platform for archaeological analysis and documentation (Diara & Rinaudo, 2021). While in some other cases, these applications have been implemented for preventive archaeological projects, for instance in Banfi et al. study (Banfi et al., 2020) they developed an open-source BIM platform able to merge BIM sensors, monitoring, historic building information modelling and VR, with a specific focus on complex scenarios with heritage sites subjected to flood risks and water level changes. At the same time, Saricaoglu et al. (2022) defined a method for data-driven conservation actions alongside the decision-making process to integrate both levels of geometrical accuracy and the multi-level data for the interventions.

For the industrial archaeology digital process in literature, we can find, from a larger scale, GIS approaches for the creation of databases, spatial analysis and visualization (He et al., 2015), to similar approaches related to the definition of as-built models, from UAV survey to BIM environment (Barrile et al., 2019). In particular, there are some cases where the main focus is the machine apparatus inside the former factories. The integrated survey process of the main components of this architecture type is followed, in one case by an HBIM modelling with a deepening aspect of LOD (Currà et al., 2022), in one other with the creation of a virtual tour (Shults et al., 2019).

Hence, the literature review shows a clear gap in documenting industrial archaeology and the historical manufacturing processes. Furthermore, the applications could be more extensive in the data representation and relation between different domains to address the possibility of making interdisciplinary concept correlations. These gaps represent the starting point for our study which tries to delineate an approach towards industrial archaeology and other archaeologies by considering its valuable aspects, defined in the next paragraph, and through the integration with semantic web technologies to overcome the evident difficulties in the investigation process of a complex heritage site.

2. COMPLEX ARCHITECTURES OF MULTIPLE ARCHAEOLOGIES: RESEARCH, DOCUMENTATION AND INVESTIGATION PROCESSES

Complex architectural sites, defined by the stratification of multiple archaeology, are a peculiar heritage field rooted in the Lazio region. The Sanctuary of Hercules and the former Segrè Paper Mill site in Tivoli – selected case study for our research - are unique evidence of the past Roman empire that crossed centuries up to industrial time. In fact, the actual state is a combination of classical and industrial archaeology. In this case, the main focus of the study regards the semantic definition and knowledge modelling of the industrial processes of the Segrè papermill, which is the latest industrial reuse of the Sanctuary, built for some parts of the former manufacturing structures such as the ironworks and the powder magazines. This area stands mainly between the podium and the northern portico, made of iron and reinforced concrete structures. Although quite invasive, the different reuses over the centuries contributed to preserving the porticos dated II century B.C. A second expansion occurred in the former ironworks, where another paper machine expanded the production cycle (Cairoli & Ten, 2016). The plant had an automated production, and hydroelectric turbines followed later on by an electric cabin serving it. The whole complex was decommissioned in 1956, and today, it is partially reused as a museum.

The factory, machines, objects and documents are explored as part of a system that has historically, socially and economically determined the territory and has shaped the landscape. The evidential value reflects activities that had and continue to have profound historical consequences and is based on this evidence's universal value (TICCIH, 2003). Moreover, the social and cultural aspects are related to an industry, a specific company, an industrial community or a particular trade or skill. It may also carry technological and scientific value in manufacturing, engineering and construction history or have aesthetic qualities deriving from its architecture, design or planning (Douet, 2016). Therefore, documenting the industrial processes represents a way to enhance the possibility of continuously perceiving its values and to highlight, in this specific case, how the multiple stratifications and different industrial reuses have helped maintain the ruins of classical archaeology for centuries. The purpose is to give valid support in the digital processes for built heritage by leaving intact the specific features and historical evidence of different periods, actively working to enlighten these diversities during the intervention and valorization activities. It is not a simple and pure conservation process since the past transmission proceeds through its continuous re-interpretation and through a global and interdisciplinary approach.

3. KNOWLEDGE BASE FOR HISTORICAL ARCHITECTURE AND INDUSTRIAL PROCESSES

3.1 Ontology development methodology

The first step to develop the knowledge-based system is choosing the most appropriate methodology that best addresses the specific case study. As described in paragraph 2, it is necessary to define and consider representation from multiple domains, in particular, it is compelling to highlight how the whole process interacts with the existing and new building spaces, related to different evolution phases and how it is combined with the other archaeology and study fields. Some ontologies already cover parts of the domains of interest, while in other cases, integration of new representations schemas is needed to provide a full coverage of the information for a complete comprehension of the artefact.

In the ontology engineering discipline and, more recently, in its application in the AECO field, the Linked Open Terms (LOT) methodology has recently been introduced and developed from the NeOn methodology (Suárez-Figueroa et al., 2015), which places particular emphasis on the reuse of existing ontologies - both general and domain ontologies - already prevalent in the relevant industry, fostering interoperability and optimizing the definition of concepts, attributes and relationships. In a field as complex as multiple archaeology, the potential benefits of such a methodology are clear: the presence of different disciplines involved, seemingly far apart, with their terms, concepts and general knowledge structures, requires, first of all, an effort of correlation between the various domains and, secondly, the work of building the missing knowledge networks or adapting the existing ones. In the specific object of this study, for example, the reuse and integration of ontologies dedicated to the representation of construction and buildings, those dedicated to the documentation of cultural heritage, and those used to describe industrial processes and/or production facilities are important.

3.2 Ontology requirements specification

The use case and purposes concern the documentation of archaeological and industrial heritage to support the investigation and knowledge processes for the intervention and recovery of complex palimpsest. The data exchange needed for this study is based on different sources. All the information necessary for this study has been gathered from many sources starting from a historical and archival study composed of written sources and cartographic, iconographic and photographic ones from the two central archives (Segrè family and Emo Salvati). Besides these historical studies, it is essential to combine them with the archaeological ones, that is, the analysis of all the remaining on surfaces and excavation necessary to reconstruct the whole industrial process. The data acquisition through an integrated survey is then combined with the information collected through the other sources to get a complete information framework.

The *non-functional requirements*, which refer to the characteristics, qualities or general aspects, can be identified by defining a system able to manage heterogeneous data from multiple domains, to assure flexibility, adherence and coherence. Furthermore, consistency should be considered to avoid duplicate information or over-constrained property assertion. Extendibility can be achieved by using standardized languages and existing patterns and concepts for ontology development (Suárez-Figueroa et al., 2009). For scientific data management, the ontology should also be findable, accessible, interoperable and reusable.

The *functional requirements* are the ones related to the use case. The documentation of industrial processes requires the definition of the activities performed in the process stages and the different resource types used (machines, humans, raw materials, semi-finished products). A detailed description of each production stage is necessary for a comprehensive understanding of the process, the machines and the humans/workers, all valuable and fundamental aspects for documenting and investigating industrial archaeology. Along with defining the manufacturing activities, the ontology needs to determine the spaces or rooms where the activities used to be performed, in terms of architectural and technological aspects through spatial and technological entities and the relation between production process, machines and building components and spaces. Layered archaeologies are complex sites where interpretation is usually a complex activity. Therefore the representation of the evolution phases should concern the whole complex and single building elements to interconnect these three domains of interest in an interdisciplinary way by covering all the knowledge useful for the intended documentation activity.

3.3 Ontology conceptualization

From the sources listed in paragraph 3.1, the first attempt in the conceptualization work was to delineate the complete cycle highlighting classes or concepts necessary to describe the whole production system.

In 1935 the mill was expanded, presumably introducing this cycle. The raw materials used for paper making were rags and wood logs. The process based on the rags, our main focus in this case, started from the arrival at the factory in bales where they were stacked temporarily in large deposits. The processing of rag consisted of cleaning and sorting according to various qualities and cutting them in special cutting machines. Once they were selected and separated, they were cleaned a second time by tumblers and beaters, then shredded and leached under pressure with lime or soda in spherical or cylindrical kettles. These operations were followed by fraying in Hollander piles, sort of tanks filled with water where a cylinder with knives reduced the rags into filaments. After that, the produced “half pulp” was conveyed in special tanks and subjected to bleaching with calcium chloride before being fed into the Hollander refining machines. In the Hollander refiners, the half pulp was beaten by other rotating cylinders and converted to “all pulp”, ready to be transformed into paper. Thus the pulp was coloured and glued with resin soap to give texture and to prevent ink from spreading on it. In the paper machines, the pulp was stretched into a thin layer of thick water on a wire cloth, which was then detached into a veil and it was passed over a long woolen felt around a series of huge drying cylinders, heated by steam, and finally dried, it was rolled up as a raw product .

The long ribbons produced by the paper machines were directly pressed and smoothed by giant calenders and then passed to the rolling machines. In the preparation rooms, the paper was cut into sheets and reams were assembled; in the end, the sheets were sorted one by one to be packed and shipped or for other finishing works.

Space	Activity description	Input components	Activity requirement	Resource in Automatic solution	Resource in manual solution
-	1. wood defibration	wood logs	handling tooling (machines) loading	mechanical defibrators	operator, power tool
rags room	2. rags sorting and preparation	raw rags	handling tooling (machines) workholding	hedge cutter cement sack dusting shredder Lannoye	operator
half pulp processing area	3. under pressure leaching	cleaned rags lime soda	handling tooling (machines)	spherical boiler	operator
half pulp processing area/hollander beater room	4. fraying and pasting	impurity-free fibers resin soap water	handling tooling (machines)	hollander beater for fraying hollander beater for pasting	operator
half pulp processing area/hollander beater room	5. whitewashing	"half" pulp calcium chloride	handling tooling (machines)	hollander beater for whitewashing	operator
half pulp processing area/hollander beater room	6. refining	whitened pulp	handling tooling (machines)	hollander beater for refining	operator
paper machine room	7. unfold the paper	pulp	handling tooling (machines) workholding	paper machine	operator
preparation and finishing rooms	8. pressing, smoothing, cutting, packaging	raw paper	handling tooling (machines) workholding	Haubold rotary cutter winding machines packaging presses calender	operator Diamont paper cutter and cutting table Verny rectangular cutter turntable
Paper sorting room	9. paper selection	commercial paper	handling workholding	-	operator

Fig. 1: Use case data of the latest production process of the Segrè papermill.

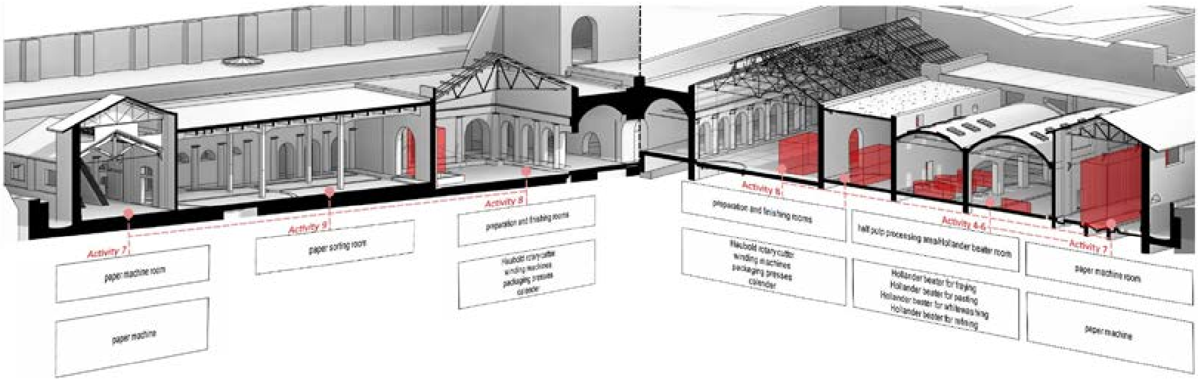

Fig. 2: Spaces, activities and machines in the latest Segrè papermill production process. BIM model carried out by Andrea De Pace and Riccardo Rocchi under the supervision of Edoardo Currà.

Based on the studies conducted by Sanfilippo et al. (2021), we detailed the definition of the process plan, the set of sequential activities decomposing the process, the input component or materials for each activity and the requirements to execute each activity. As shown in the figure, table 1 defines the critical aspects of the use case by listing the activities and their description, input components of each activity, and resources needed to execute each activity, which can be subdivided into manual and automated resources.

After that, it was necessary to identify key concepts to relate the papermill cycle with the building spaces where it used to be performed, which is represented in the first column of Figure 1. The spaces and the building components are required to describe the different halls built in overlapping periods of time. For this reason, it is fundamental to briefly sum up the significant historical stages of the investigated area and, consequently, the evolution of the construction methods related to the different phases. As we already have introduced, the latest industrial production was installed in the northern portico and sacred area of the Sanctuary of Hercules. Over the centuries, many different productions and constructions intersected. In particular, in the 1920s, the mill already had three paper machines, with a layout maintained until its dismission. Between 1923 and 1926, took place the elevation and expansion of the paper machine room in the sacred area. Thanks to the new technologies, a radical change occurred in the 1930s through the widespread use of reinforced concrete structures and prefabricated frames for large roofs.

In this period, the rag room was renovated and expanded, preceding the construction of a paper storage room and a paper sorting room on a two-level building. During the war, the roofing of the sacred area rooms suffered substantial war damage. Three wooden truss roofs were replaced with reinforced concrete structures and two barrel vaults with SAP technology. Overall, there was no real expansion but a simple consolidation of the overall preexisting layout. In Figure 2 some of the spaces/areas, activities performed and machines are represented in the informative model.

Once the main domains, concepts and classes are described, the following step of this study, detailed in the next paragraph, concerns the research and reuse of existing ontologies and the encoding activity.

3.4 Ontology reuse and encoding

The three domains considered for this case study are the *Production Process*, the *Architectural Artefact* and the *Historical Evolution* and they are all connected since the process and the manufacturing tasks are performed in specific spaces that belongs to different areas or rooms of the site which are built in various phases of the papermill production. After reviewing the existing ontologies for all the listed domains we used for the Building spaces and elements the IFC Standard, while for the production process we chose an extension of the IFC and the FA ontology that is mainly focused on the relation between the used resources and activities performed. For the historical evolution documentation we based the whole reconstruction process on the CIDOC-CRM (Fig. 3).

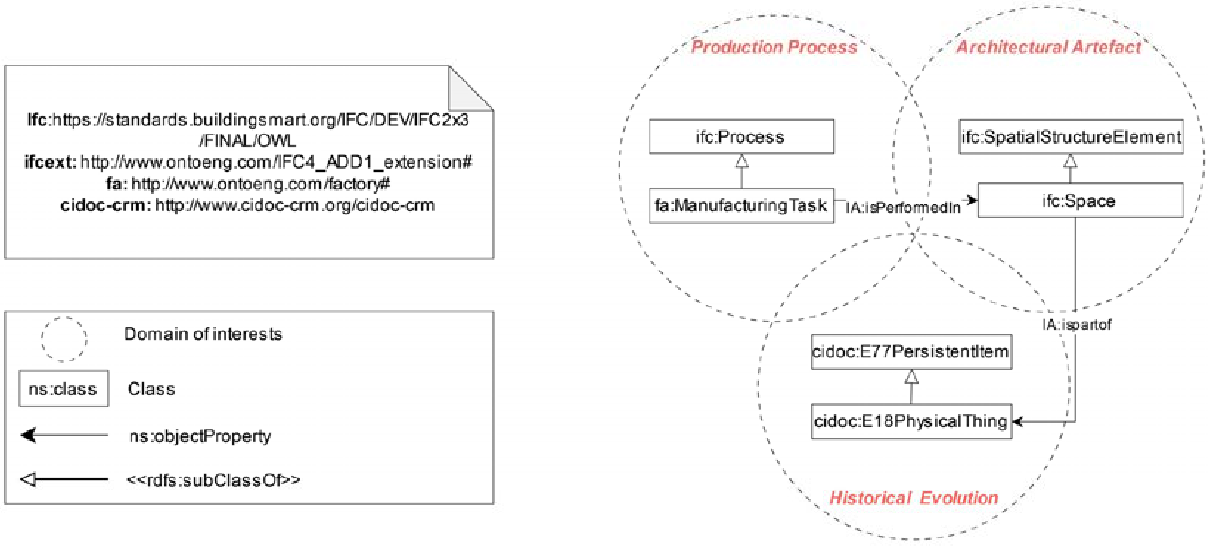

Fig. 3: Knowledge modelling of the three domains considered: the production process, the architectural artefact and the historical evolution.

The chosen ontologies for the production process modelling provide an extendible representation of the factory entities related to production systems, resources and products. The starting point was a simplified version of the IFC based on two main classes. A process (*ifc: IfcProcess*) "is an event that transforms input-output products while making use of resources under specific control rules. A resource (*ifc: IfcResource*) represents an entity that is needed to perform the process. In turn, various objects, such as physical products, people, and materials, can be employed as resources". Then we integrate this approach with the one proposed by Sanfilippo et al. (2021). They started considering three existing high-level approaches and trying to unify them in a single and complete framework. In this way, it was possible to consider and represent manufacturing by taking into account activities, goals and activities occurrences during the entire process since the IFC-based modelling is not able to distinguish alone between the entities and their relations. On the other hand, through this integrated methodology, the properties are explicitly stated, and they can provide a useful explanation of the case study. For instance, the *activity description* is a class that describes the specific manufacturing process description where *whitewashing* is an individual and refers to conveying the *half pulp* in special tanks and subjected to bleaching with calcium chloride. The *input components* for each activity list the components needed for that singular operation and they are detailed through the property *hasComponentReq*. For the activity whitewashing, the input components are *half pulp* and *calcium chloride*, and the output of the same activity, which is expressed through the propriety *hasOutput* is the *whitened half pulp* that is combined with other components and becomes the input resources of the next activity. The activity requirements list the resources and capabilities that are necessary to perform specific tasks. For instance, the whitewashing activity *hasResourcesReq tooling* and *handling* that are individuals of *CapabilityDescr*. The *Resource in Automatic solution* and the *Resource in Manual solution* list the description of resources either in the automatic or manual configuration that can execute the activity; *Whitewashing Hollander machine* and *Operator* satisfy the two resource requirements and are correspondingly individuals of *ArtifactDescr* and *Descr*.

The production process domain and the building artefact domain are connected since the *fa: Manufacturing Task*, a subclass of *Ifc: Process*, *isPerformedin* a specific place of the papermill complex. In fact, the architectural artefact knowledge modelling started from the class *Ifc:IfcSpace* which is defined as "an area or volume bounded actually or theoretically. Spaces are areas or volumes that provide for certain functions within a building". The main classes considered are both subclasses of the *Ifc:IfcProduct*, in detail, the *Ifc:IfcBuildingElement* indicates "all elements that are primarily part of the construction of a built facility, i.e., its structural and space separating system. Building elements are all physically existent and tangible things". The latter class was useful to describe the building components, and it was divided into *Load Bearing Skeleton* itself subdivided into *Steel Frame* and *Concrete Frame*; *Horizontal Closures* divided into *Horizontal Base Closing*, *Horizontal Intermediate Closing* and *Horizontal Top Closing* that can be Plane, Sloped or Curved; and *Vertical Closures*. For instance, considering the manufacturing task *whitewashing,* it was performed in the *Hollander Beater Room*, an individual of *Ifc:IfcSpace*, and it is enclosed in *Industrial floor1* as *Horizontal Base Closing*, and *Barrel Vaults* as *Horizontal Curved Closing*, which replaced the *Horizontal Sloped Closing Wooden Truss Roof* that was damaged during the second world war. For the *Vertical Closing*, we identified two different closings instantiated as *Tuff Wall 1* and *Tuff Wall 2*, probably built in two different periods, and they have incorporated the structures derived from the Hydroelectric and hydraulic canals Construction.

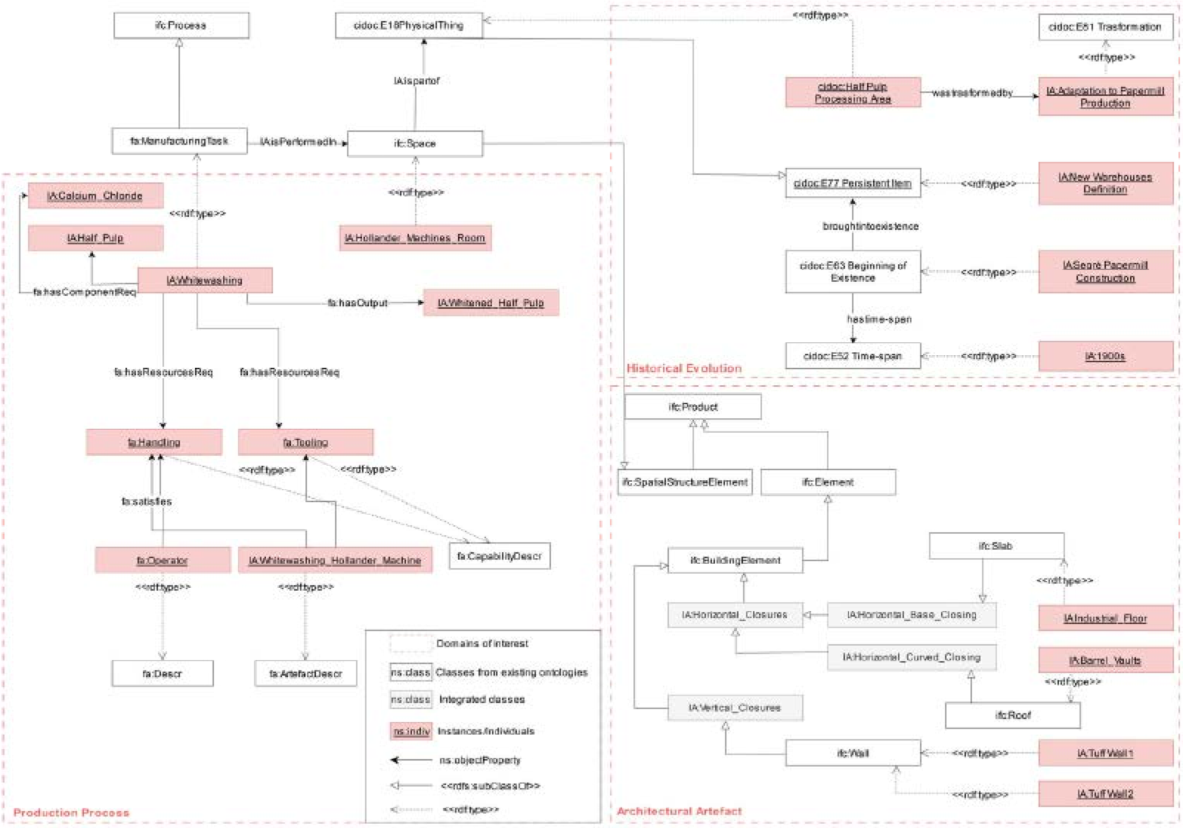

Fig. 4: Instantiation process of the whitewashing activity performed in the Hollander Beater Room.

Moreover, the building construction phases are very intricated due to the multiple overlapping structures, and therefore a clear explanation is necessary for a deep understanding of the artefact elements. For this reason, the Spaces defined in the architectural artefact domain are connected with its historical evolution through the property *ispartof,* that associates the *Ifc:IfcSpace* with the E18 class of the CIDOC-CRM *PhysicalThing*. As explained in paragraph 1.1, the CIDOC-CRM provides a common and extensible semantic framework for evidence-based cultural heritage information integration. The classes used are E18 Physical Thing appropriate for the definition of different rooms where the production process took place, i.e. the *"Half Pulp" processing area*. The E18 is a subclass of the E77 Persistent Item, which defines items with a persistent identity, sometimes known as "endurants" in philosophy. For example, in our case, it could be interpreted as *New Warehouses Definition*, considering the latest papermill production. E66 Beginning of Existence is instantiated as *Papermill*

Construction and it is connected with the E77 Persistent Item through the propriety *hasBroughtintoExistence* and through the property *hasTimeSpan* it is related to E52 Time-Span instantiated as 1900s. Those classes are fundamental to documenting a specific state of the artefact, and we also considered other CIDOC classes to document the transformations that modified the physical structures and also functions. To express the transformation, we considered E81 Transformation, instantiated as *Adaptation to Papermill Production.* Other more detailed classes and proprieties can be helpful, such as E11 Modification and its subclasses E79 Part Addition and E80 Part Removal, which can be directly related to the E18 Physical Thing through the propriety *hasModified.*

In Figure 4 is represented a small portion of the instantiation process which regards one of the activities performed in the Hollander Beater Room. All three domains are represented and are interconnected with each other. Each single manufacturing task is then connected with the following tasks through the input components defined as Component requirements and the outputs which are the input of the subsequent activity. The tasks are then connected with the spaces and the historic evolution domain as explained above. As defined in the picture, we combined classes from existing ontologies with integrated classes, we represented the individuals of each class in red, correlating them with object properties.

4. INTEGRATING KNOWLEDGE-BASED REPRRESENTATION AND HISTORIC BUILDING INFORMATION MODELLING

The knowledge formalization related to the latest papermill production, which includes the disciplines presented above, is then integrated with geometrical and technological aspects of the artefact components. The first connection between the knowledge structure and the informative model has been made through the correlation between the *Ifc:IfcSpace* of the knowledge base and the *Ifc:IfcSpace* of the BIM model. The IfcSpace is defined, for our case study, as the rooms or areas where the activities were performed. The integration of the two models is a critical process. It is necessary to carefully decide which information can better connect these two environments to ensure interoperability and data alignment.

In the BIM environment, each room has a label, for instance, *Paper Machine Room* or *Hollander Beater Room*, individuals of the *IFCSpace*. The label correspondence is between the name of the room in BIM and the individuals of the knowledge base *Paper Machine Room* or *Hollander Beater Room*, instances of the *IfcSpace* Class.

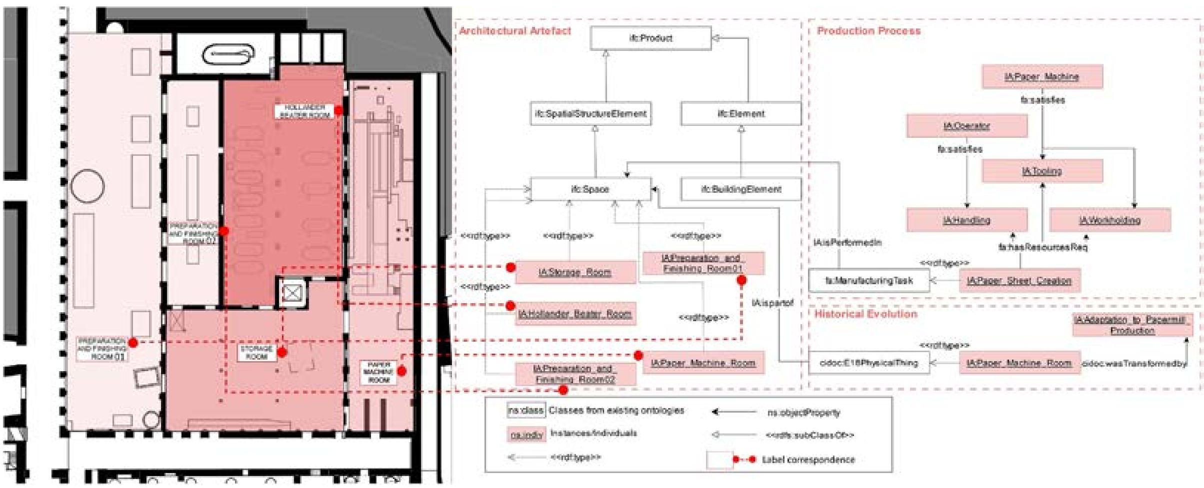

Fig. 5: Label correspondence between the rooms in the model and the individuals in the knowledge base.

The label corresponding process is represented in Fig. 5, through this integration activity is possible to underline a fundamental aspect of this approach. In fact in this way, we can connect the entities with other concepts, abstract or concrete which belongs to different domains in a cross disciplinary way. Using only the BIM representation schema is quite limited since many relations and concepts cannot be fully interpreted and represented. This approach can answer some of the critical issues related to the current practices in the digital built heritage processes. The documentation of the artefact requires the representation of a broader domain of knowledge, which includes extremely diverse and specific aspects such as historical, cultural contexts, construction techniques, and the history of materials which guide its accurate interpretation. Therefore it is possible to represent and manage information from an incremental and recursive perspective and from heterogeneous sources. The complex nature of built heritage fields needs appropriate tools and approaches to better address the multiple and open issues.

While in the first case, the label correspondence was between spaces and rooms, in this second case, we focused on the building elements. The *ifc* schema has a rigorous hierarchy representation, and sometimes to represent the heritage buildings, we are forced to use this schema even if it does not address the singularity and uniqueness of these artefacts. The building components of a historical building may not precisely correspond to specific classes in the *ifc* structure, especially when considering overlapping structures where every element may have acquired different meanings and functions over time, embedding a wide range of historical, cultural, social and technological values. In Figure 6, we can see the label correspondence between the two models by considering some of the building elements. For the architectural artefact representation, it was included in the knowledge base another class level as a subclass of the *ifc:BuildingElement* defined by *Ia:HorizontalClosures* subdivided in *Ia:HorizontalBaseClosing* and *Ia:HorizontalSlopedClosing*, and *Ia:VerticalClosures*. The instantiation process represented within the red boxes in the diagram is conformed to the individuals in the BIM model, which are likewise instances of *ifc:Wall*, *ifc:Slab* and *ifc:roof*.

The possibility of correlating concepts outside the informative model helps us to represent the authenticity of the heritage artefacts, the overlapping structures of the building components, the inconsistencies, and the different interpretations of single or multiple elements. These are all steps of the documentation and investigation processes that all the specialists perform in their field and, through this integrated approach, can be represented consistently in a machine-readable way.

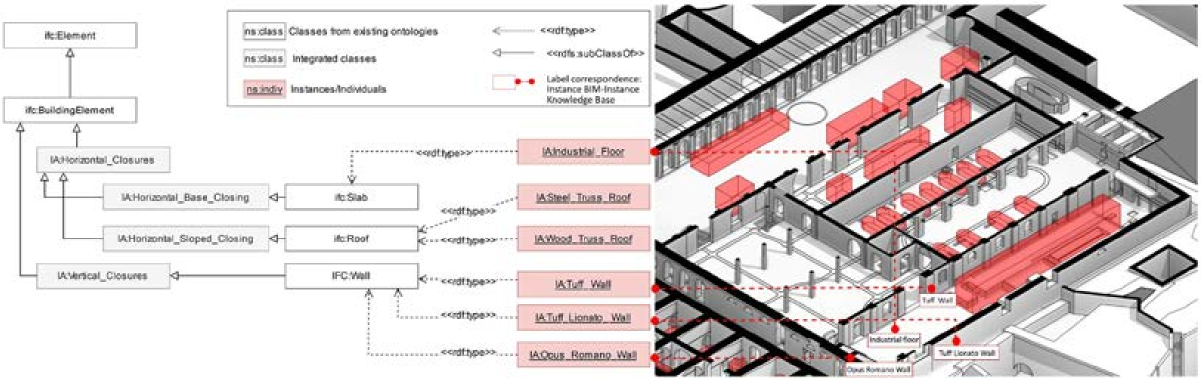

Fig. 6: Label correspondence between building elements in the model and the individuals in the knowledge base. BIM model carried out by Andrea De Pace and Riccardo Rocchi under the supervision of Edoardo Currà.

5. CONCLUSIONS

This research focuses on modelling the main features of industrial archaeology in a multi-layered historical site. We developed a structured knowledge base integrated with the BIM model to document the latest papermill production of the Segrè family. The historical industrial process and the manufacturing machines have shaped over time the architectural assets built on the remains of the Roman sanctuary and the former iron and powder productions. The knowledge base creation started by defining the domain of interests: production process, architectural artefact and historical evolution, followed by the knowledge base creation through an ontology conceptualization, reuse and encoding activities. Finally, the last part deals with integrating the knowledge base with the informative model made through a label correspondence between the same IFC classes.

The novelty of this integrated approach addresses some issues presented in section 1. Starting from a clear gap in the digital documentation process of the industrial heritage field, we proposed a methodology for the knowledge representation that considers all the domains of interest, with a specific focus on the industrial process, to customize the existing ontological approaches for contemporary manufacturing and Industries 4.0. Over time, the aggregated work on multiple industrial heritage sites can extend the queries on a large amount of data and scale to define similarities through the use of computable knowledge, highlighting differences and multiple interventions and recovery actions based on regional and transnational cases of industrial archaeology.

The application and validation of the proposed approach in similar contexts are necessary to highlight improvement aspects, extend the concepts and relations of the considered domains, and implement other valuable domains. Moreover, the difficulties faced during the knowledge acquisition process, caused by data inconsistency and uncertainties, could be managed by new ways of knowledge representation systems able to document and grade multiple interpretations schemas. Indeed, the following step of this research is to overcome the above-presented limits of this approach to better represent and manage the built heritage knowledge.

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LINKED DATA FOR THE CATEGORIZATION OF FAILURES MECHANISMS IN EXISTING UNREINFORCED MASONRY BUILDINGS

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ABSTRACT: *Assessing the structural integrity of unreinforced masonry structures is a complex and time-consuming process that necessitates the knowledge of various experts and meticulous cross-referencing of diverse data to achieve a comprehensive understanding of the building. In recent years, the Architecture and Construction Industry has witnessed a digital transformation, largely driven by Building Information Modeling (BIM). BIM has proven immensely valuable in the conservation of historic buildings. However, while it excels in new construction projects, its full potential is not fully realized when dealing with existing structures. A clear example of this limitation can be observed in the Industry Foundation Classes (IFC) format, which lacks instances necessary for accurately representing existing building features. This research contribution aims to advance the process of semantic enrichment of BIM for existing buildings, building upon findings from existing literature. Leveraging the Linked Data Approach and utilizing both existing ontologies and newly proposed domain ontologies, the objective is to facilitate the identification of vulnerabilities and potential local failure mechanisms. The geometric information of the building is represented in the IFC STEP format and enriched semantically by establishing new relationships between classes that are not present in the standard IFC. This approach is applied to a case study in the historical center of Castelnuovo di Porto, Italy. The results of this work demonstrate how the proposed model, enhancing the BIM representation of existing buildings and enabling better identification of potential weaknesses, contributes to improved preservation and seismic resilience of historic structures.*

KEYWORDS: *BIM, Linked Data, Semantic Modeling, Historic Constructions, Structural Masonry.*

1. INTRODUCTION

Before the advent of modern construction techniques, buildings were raised employing local materials and construction methods, resulting in a large percentage of the built heritage being composed of unreinforced masonry structures. The effectiveness of unreinforced masonry constructions depended on adhering to a set of empirical rules known as the 'rule of the art (Antonino Giuffré et al., 2010). This aspect becomes particularly critical in seismic scenarios, as past seismic events demonstrated that following the 'rule of the art' ensures walls exhibit a *monolithic behavior*, fundamental to being resistant to earthquakes. Furthermore, the proper connection between structural elements is another critical factor that helps prevent out-of-plane local failures. These failures can happen when walls or portions of walls collapse outward during an earthquake, posing a significant danger to both the structure and its occupants (Antonino Giuffré, 1993; Antonino Giuffré et al., 2010).

The Italian Code, which is a major reference for the assessment of historic buildings, provides three levels of analysis of the structural behavior of existing unreinforced masonry buildings: (i) Identifying the shear strength of the masonry under examination, (ii) Verifying local mechanisms, and (iii) Conducting global numerical analyses. (Norme Tecniche per Le Costruzioni, 2018). The three levels of assessment become increasingly more comprehensive, with their accuracy contingent on the modeling assumptions. Consequently, opting for the simplest level of assessment would be preferable when knowledge is limited.

Considering these principles, a precise evaluation of the structural behavior of existing non-reinforced masonry buildings, utilizing more advanced methods, necessitates a thorough examination of the structure, involving

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Maria Laura Leonardi, Stefano Cursi, Daniel V. Oliveira, Miguel Azenha, Elena Gigliarelli, *Linked Data for the Categorization of Failures Mechanisms in Existing Unreinforced Masonry Buildings,* pp. 781-790, DOI 10.36253/979-12-215-0289-3.78

experts from diverse fields. (ICOMOS, 2005). Consequently, a systematic methodology is needed to allow the integration of data of different types, avoiding the repetition or defeat of pivotal information.

With the introduction of Building Information Modeling (BIM), the architecture and engineering industries have significantly changed their processes. This technology, although it was developed for the construction of new buildings, has not gone unnoticed in the field of rehabilitation of historic buildings. Today, the term HBIM (Historic Building Information Modeling) identifies the application of BIM technology to historic buildings (Maurice Murphy et al., 2009). The HBIM methodology has been explored as support to various areas of conservation (Pocobelli et al., 2018; Volk et al., 2014). Relevant efforts have been done to improve the representation of complex geometry, mainly with the integration of advanced survey acquisition methods (Cotella, 2023). HBIM applications exploit the potentiality to map damage and deformation accurately (Barontini et al., 2022; Moyano et al., 2022), conduct simulations (Gigliarelli et al., 2017; Ursini et al., 2022), manage the intervention on site (Biagini et al., 2016) and optimize facility management (Piselli et al., 2020).

Despite its widespread use, HBIM encounters challenges in its application, mainly because the original BIM methodology was primarily introduced for new construction projects. In reality, even the use of Industry Foundation Classes (IFC) needs to be enhanced to digitize existing constructions. Consequently, the semantic enrichment of HBIM models has emerged as an increasingly researched area. Due to the multidisciplinarity of the conservation field, the use of Semantic Web Languages through a Linked Data approach is gaining momentum (Cursi et al., 2022). The advantage of this methodology is that it allows modeling domain-specific information using specialized ontologies, which can be employed as external links to enhance the content of the BIM models.

From a broader perspective, the use of semantic web standards such as Resource Description Framework (RDF) and Web Ontology Languages (OWL) has the advantage of providing interoperability between data of different domains which are published on the web. On the other hand, IFC is written in EXPRESS language, and has a strong emphasis on the tridimensional representation of the geometry, while remaining difficult to integrate with other web sources (Rasmussen et al., 2020).

The ifcOWL ontology has been a pioneering attempt to extend the content of IFC to the semantic web (Beetz et al., 2009). However, due to its extensive length and complexity, it becomes challenging to implement and utilize in practical applications. As an alternative, other more contained ontologies have been proposed to represent construction instances in the semantic web. Under this approach, spaces are defined using the Building Topology Ontology (BOT) (Rasmussen et al., 2020), building elements with the Building Element Ontology (BEO) (Pauwels, 2018), and materials with the Material Property Ontology (MAT) (Poveda-Villalón & Chávez-Feria, 2020). The tendency of *modularization* of information based on different domains also interested the BuildingSmart Technical Room. Indeed, for the next generation of IFC, it is proposed to have a common base layer, connected to several extensions belonging to different domains (Berlo et al., 2020). In addition, the IFC base schema will be language-independent, ensuring greater interoperability with formats currently in use in other fields, including RDF.

In the past, there have been proposals for large and complex ontologies to represent historical data. The CIDOC-CRM for instance (Crofts et al., 2003), has been mainly developed for museums, but then extended to other domains such as the representation of non-destructive testing techniques (Kouis & Giannakopoulos, 2014), annotation of degradation phenomena of stones (Veron et al., 2015), and also for the semantic enrichment of HBIM models (Acierno et al., 2017). However, currently also in the field of historic constructions, there has been a recent preference for using a network of modular ontologies instead of a single complex ontology (Bonduel, 2021). This facilitates the better management of the ontology and the connection with different domains.

This paper aims to propose a method to digitize current methods for structural assessment of existing unreinforced masonry buildings. The purpose is to improve the management of the alphanumeric data associated with three-dimensional models, stressing standardization and interoperability. Two new domain ontologies are proposed: (i) Historic Masonry Ontology (HMO); (ii) Failure Mechanism Ontology (FMO). The first represents masonry material, while the second represents the vulnerabilities associated with specific types of masonry collapse. The two ontologies can be used together or combined with other domains. In particular, they can be used for the semantic enrichment of BIM models, combining geometry representation and alphanumerical data. This is demonstrated using a web app to map IFC and Turtle files (A. Donkers et al., 2023).

This paper is organized as follows. After this introduction, the next chapter is 'Materials and Methods', followed by 'Results and Discussion', and 'Conclusions'.

2. MATERIALS AND METHODS

From a structural point of view, masonry is a heterogeneous material, constituted by *units* and *joints*. Units are bricks or stones which actively contribute to the load-bearing capacity and stability of the wall. Joints are the junctures between masonry units and can be either dry or filled with mortar. The most resistant masonry should have an arrangement of discrete elements such that monolithic behavior is ensured.

When the wall exhibits monolithic behavior, structural simulations can be conducted by considering a corresponding homogeneous material. However, even in such cases, the wall's morphology needs to be assessed, to define the most appropriate modeling assumptions. Indeed, the Italian Building Code designates specific mechanical parameters of reference, considering the type, size, materials, and arrangement of units and joints.

With these premises, it is evident that for the structural analysis purpose, it is necessary to provide a comprehensive representation of the masonry material, considering its heterogeneous features. In the already existing representation schemas, such as the IFC or the MAT ontology, there is no possibility of having such a detailed description. Wall instances are indeed associated with 'material layers', and to each layer, it is attributed and homogeneous or even heterogeneous material, but where the different material's constituents are not defined as classes. In this way, it is possible to represent discontinuities only along the cross-section of the wall, which is not representative of the typical configuration of masonry walls (Figure 1).

To fill this gap, a new ontology was designed. This *Historic Masonry Ontology* (HMO), was conceived as a *foundation* ontology, to be used for the structural assessment of historic masonry structures, independently from the type of analysis (i, ii, or iii level). Then, based on the specific analysis level, other ontologies can be merged into the HMO. As a proof of concept, the Failure Mechanism Ontology (FMO) was subsequently developed to model the causes and consequences of failure mechanisms in masonry walls. The FMO is linked to the HMO ontology due to the relationship between masonry quality and wall vulnerability.

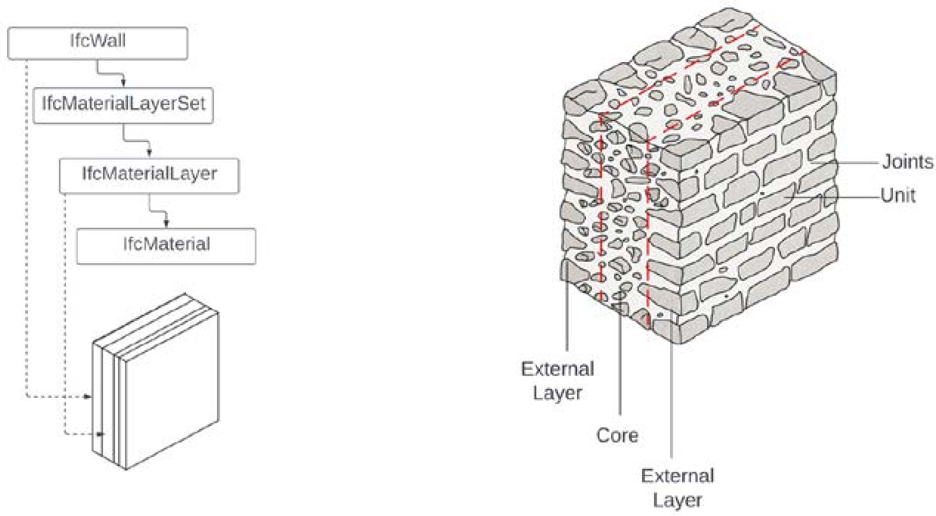

Figure 1. Morphology of an historic masonry wall compared to material modeling in IFC.

Both the HMO and the FMO ontologies were integrated with existing ontologies, exploiting the interoperability of the Semantic Web Modeling. In particular, the connection with the BEO and the MAT allows a direct mapping between the semantic model and the BIM model in IFC.

To link data between the model BIM and the model in Semantic Web Language, information is mapped between IFC model classes and corresponding ontology classes, using a common GUID. Damage elements do not have a direct equivalent in IFC, but can still be modeled as IfcElementy proxies and mapped to the ontology via GUID as well.

As shown in Figure 4, building elements, damages, and materials serve as a bridge between the IFC and the semantic model, allowing geometries to be associated with the semantic model based on the HMO and FMO ontologies.

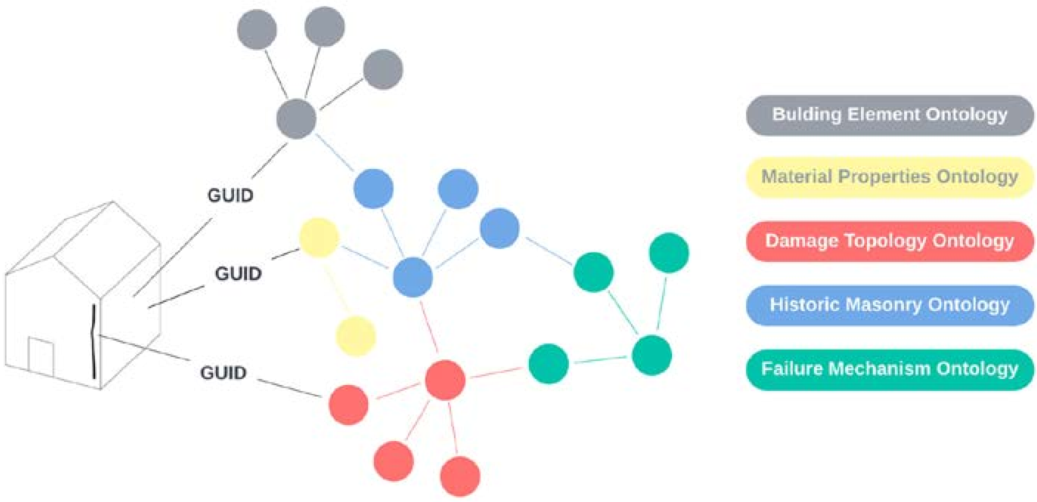

Figure 2- Methodology for the semantic enrichment of the BIM model

2.1 Historic Masonry Ontology

The Historic Masonry Ontology was implemented for the detailed modeling of masonry materials. Given the wide variety of masonry types, it was decided to propose a rather generic ontology that could be used to represent all types of masonry, regardless of units and mortar materials and morphology.

The walls are modeled with the class hmo:MasonryWall, which is a subclass of beo:Wall. The connection between the HMO and BEO ontologies is fundamental, both for interoperability between domains and semantic enrichment of the BIM models. An hmo:MasonryWall is defined by two data properties: (i) hmo:wallName and (ii) hmo:quality. The hmo:wallName allows the identification of different masonry walls in a human readable manner; the hmo:quality is intended to provide a qualitative description of the wall's quality to represent compliance with the rules of art in a synthetic manner.

The masonry layers are modeled by the class hmo:MasonryLayer, which is related to hmo:MasonryWall by the property hmo:isLayer of, the inverse of hmo:hasLayer. Each masonry layer may contain one or more hmo:Patterns. A pattern refers to a specific section of the layer, characterized by well-defined units and joint types that can be easily standardized.

The necessity for employing more than one pattern to describe a certain masonry type becomes especially critical when attempting to represent masonry types that involve various brick resources. These diverse brick resources contribute to the formation of walls comprising units with irregular compositions, interspersed with brick elements, as shown in Figure 1Figure 3.

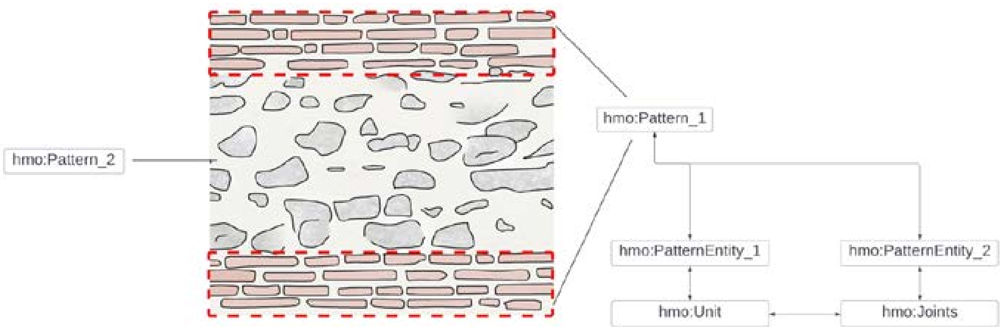

Figure 3. Elevation view of an example masonry and corresponding classes in HMO ontology modeling.

Units and joints can be modeled employing specific subclasses of the hmo:PatternEntity, which are hmo:Units and hmo:Joints. Joints are modeled as interfaces of the units, referring to the class bot:Interface. Units and joints present specific features, modeled as data properties. These classes refer in a general way to all the units and joints of the wall, so general information, such as the maximum and minimum dimensions of the units, or the horizontality and verticality characteristics of the morrtar, are assigned.

Both hmo:Unit and hmo:Joint henerith the mat:Materials from the superclass hmo:PatternEntity. The class related to the material to be associated with units and mortars does not need to be re-modeled in this ontology. In fact, it is intended to refer to and link to the MAT ontology. In addition, material characteristics can be linked to a database. This approach, derived from the Building Performance Ontology (BOP) (Donkers et al., 2021) developed for building performance assessment, is well-suited for masonry applications. The complexity of defining certain parameters leads us to rely on established Databases (Vanin et al., 2017). Finally, the ontology relates to the ontology of Damage Topology Ontology (DOT) damage, since the presence or absence of certain damage is an indicator of quality (Hamdan et al., 2019).

Figure 4 presents the Historic Masonry ontology and the link with other existing ontologies.

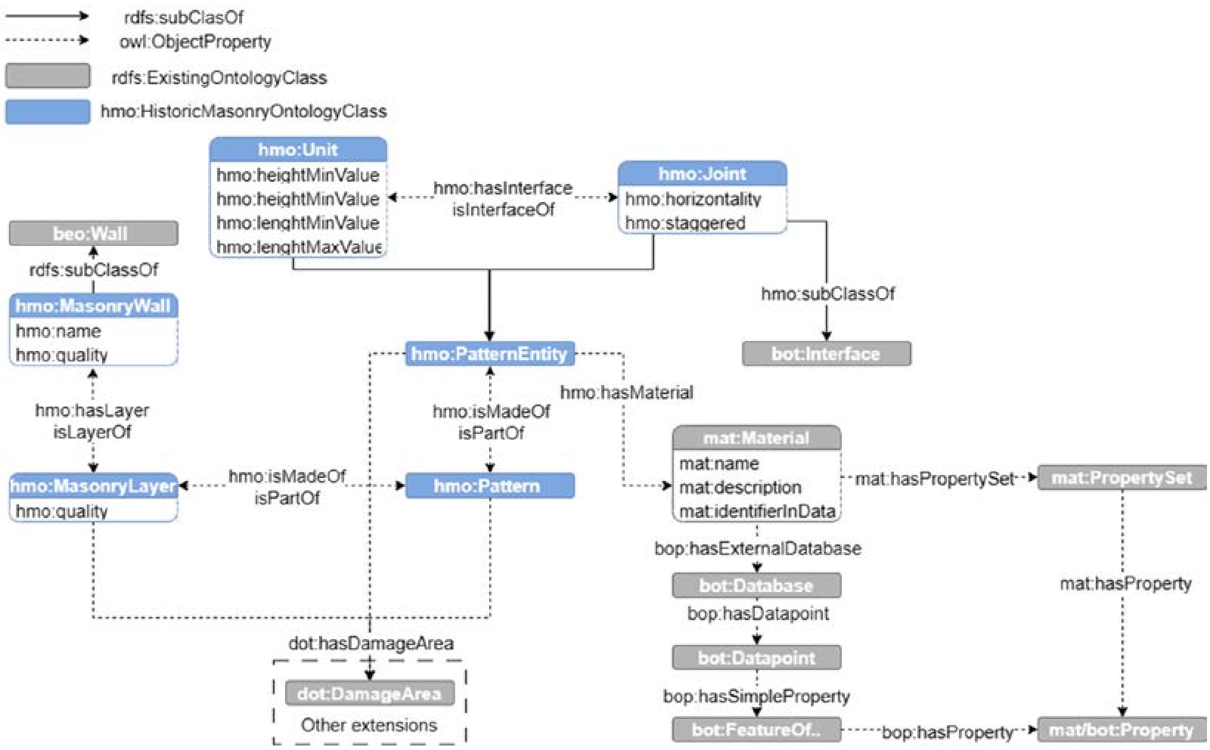

Figure 4 - Overview of the Historic Masonry Ontology

2.2 Failure Mechanism Ontology

The ontology for Failure Mechanisms enables the modeling of expected failure mechanisms by modeling the vulnerabilities that cause them.

The ontology consists of two primary classes, namely, 'fmo:Vulnerability' and 'fmo:FailureMechanism'. These classes are interconnected through the object property 'fmo:isFacilitatedBy', which establishes a relationship between mechanisms and vulnerabilities. A specific mechanism can be facilitated by one or more vulnerabilities.

To account for the qualitative nature or a combination of qualitative and quantitative aspects in vulnerability descriptions, distinct sub-classes are defined for 'fmo:Vulnerability'. This approach enhances comprehensiveness by providing dedicated classes for different types of vulnerabilities.

One of the subclasses within 'fmo:Vulnerability' is 'fmo:BadMasonryQuality', which relates directly to the previously described ontology. Defining masonry quality requires detailed description of its morphological characteristics. The object property 'fmo:isInfluencedBy' serves as a connection between the 'hmo' and 'fmo' ontologies. It is anticipated that other vulnerability subclasses can connect with various domain ontologies to address specific aspects. For example, determining whether floors are pushing and causing the presence of horizontal thrusts (e.g., 'fmo:HorizontalThrust').

Within the 'fmo:FailureMechanism' class, several subclasses exist, such as 'fmo:InPlaneFailure', 'fmo:HorizontalBending', and 'fmo:VerticalBending'. These classes require enrichment with a set of properties, which can indicate the associated load conditions for a particular mechanism. Additionally, the 'fmo:FailureMechanism' class is related to the 'dot:DamageArea' class from the DOT ontology. This relationship acknowledges that the presence of damage may be a result of an ongoing mechanism.

An overview of the complete ontology is shown in Figure 5.

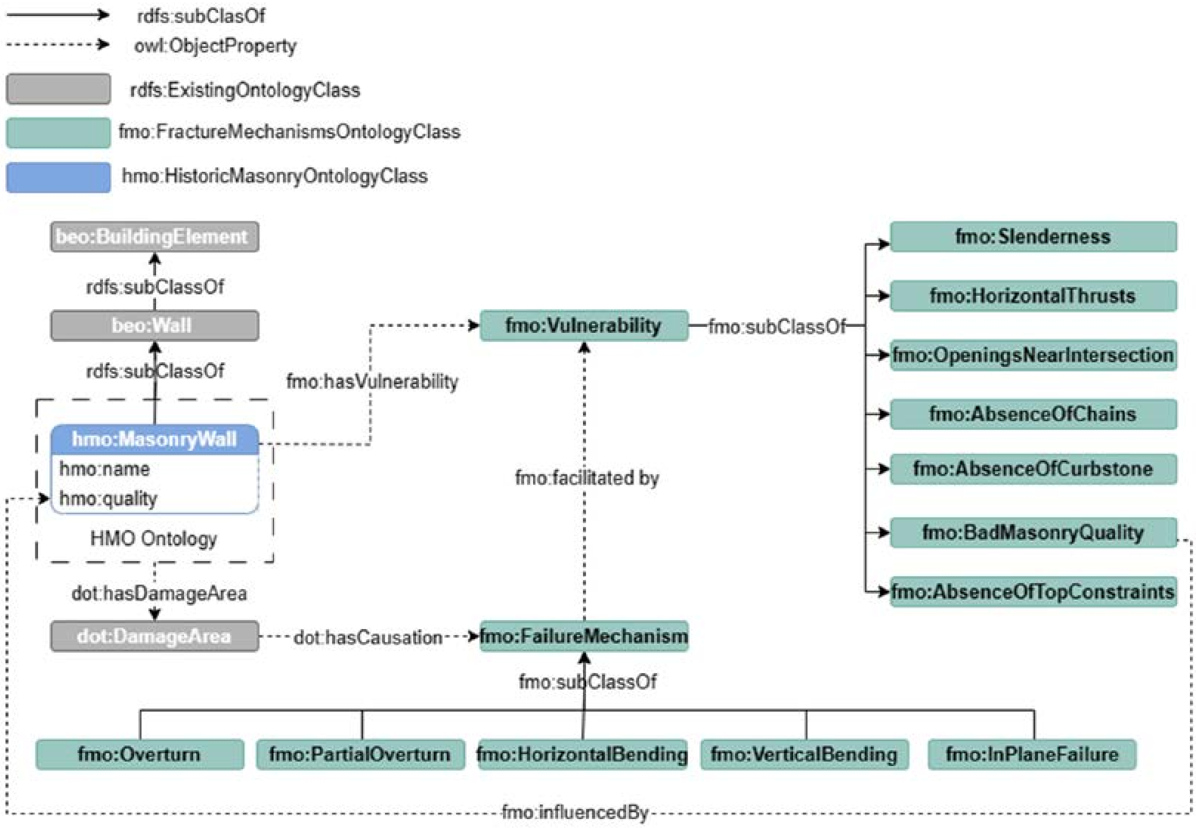

Figure 5 - Failure Mechanisms Ontology

3. RESULTS OF THE PRACTICAL APPLICATION AND DISCUSSION

To concretely illustrate the application of the proposed methodology, a residential building located in the historic center of Castelnuovo di Porto was selected. Castelnuovo di Porto is a town in central Italy known for its rich heritage of historical buildings and a diverse range of architectural styles, including residential structures, churches, and public facilities that reflect the area's rich history and architectural evolution over the centuries. The choice of Castelnuovo di Porto as a case study was driven by its structural complexity and the need to address specific challenges associated with evaluating historic buildings situated in urban environments with dense historical and cultural value.

The chosen methodological approach was particularly applied to a building that presented a set of structural and conservation challenges. This specific building, labeled as 'Wall_417_a' in the model, is part of a group of interconnected masonry structures, forming an architecturally significant complex.

In the BIM environment, the construction was modeled using proprietary software, and exported according to the IFC schema. Load-bearing walls were modeled, adding windows and doors as simple holes, modeling arches where present. Damages were included using the *IfcBuildingElementProxy* class. These elements simply serve to visualize, in the geometric model, the location of the damage. In the IFC file, there are no identified alphanumeric properties for the damages, nor any taxonomic relationship with other building elements. Regarding masonry materials, in the IFC these are identified as homogeneous, to be associated with a certain MaterialLayer.

A turtle file was created to proceed with the semantic enrichment. This particular application concentrates on the main facade of the building, referred to as 'Wall_417_a,' which is modeled using the BEO ontology. The name attributed to the façade refers to the number of the urban parcel: *417*, followed by the letter *a* as it is the first façade assessed. The wall is further represented in the model as a *hmo:MasonryWall* along with its corresponding *hmo:MasonryLayer*. Due to the initial survey's limited accessibility, only the external layer was accounted for. Therefore, the focus remained on modeling the *hmo:ExternalMasonryLayer* and associating it with a *hmo:Pattern*. The details regarding the entities of the *hmo:PatternEntity* are shown in Figure 6.

The structural damage is modeled as both *dot:StructuralDamage* and as a *fmo:Symptom*, since the presence of a crack could be a symptom of an out-of-plane mechanism. In detail, the presence of damage in one facade can be indicative of an out-of-plane mechanism occurring on the orthogonal facade. Through semantic modeling, this can be made explicit, as it was done for this model.

The roof was added to the semantic model as a *beo:Roof*, modeled as a *fmo:HorizontalThrust*, which is a subclass of *fmo:Vulnerabilities*, since a 'pushing' roof can cause the overturning of a wall. Consequently, the mechanism was modeled as *fmo:Overturning*, associating the mechanism instance to (i) the wall where it occurs; (ii) the pushing roof that caused it, (iii) the structural damage which represents its symptom.

The interactive mapping of the IFC model to the semantic model can be facilitated through web-based integration, leveraging JavaScript modules like IFC JS and COMUNICA. In this process, elements from both models are correlated using their respective GUIDs, allowing seamless cross-referencing between the two representations. This approach has been already proposed in the literature (A. Donkers et al., 2023) to query the information of the semantic model by clicking on the IFC geometry.

Figure 6 presents a comprehensive overview of what is described above. Within the IFC model, the classes corresponding to the semantic model are visually indicated by distinct colors. Notably, the semantic model consists of a network of interrelated classes, showcasing its capacity to define relationships that surpass the limitations of the IFC model. An example of the query interface is shown as well.

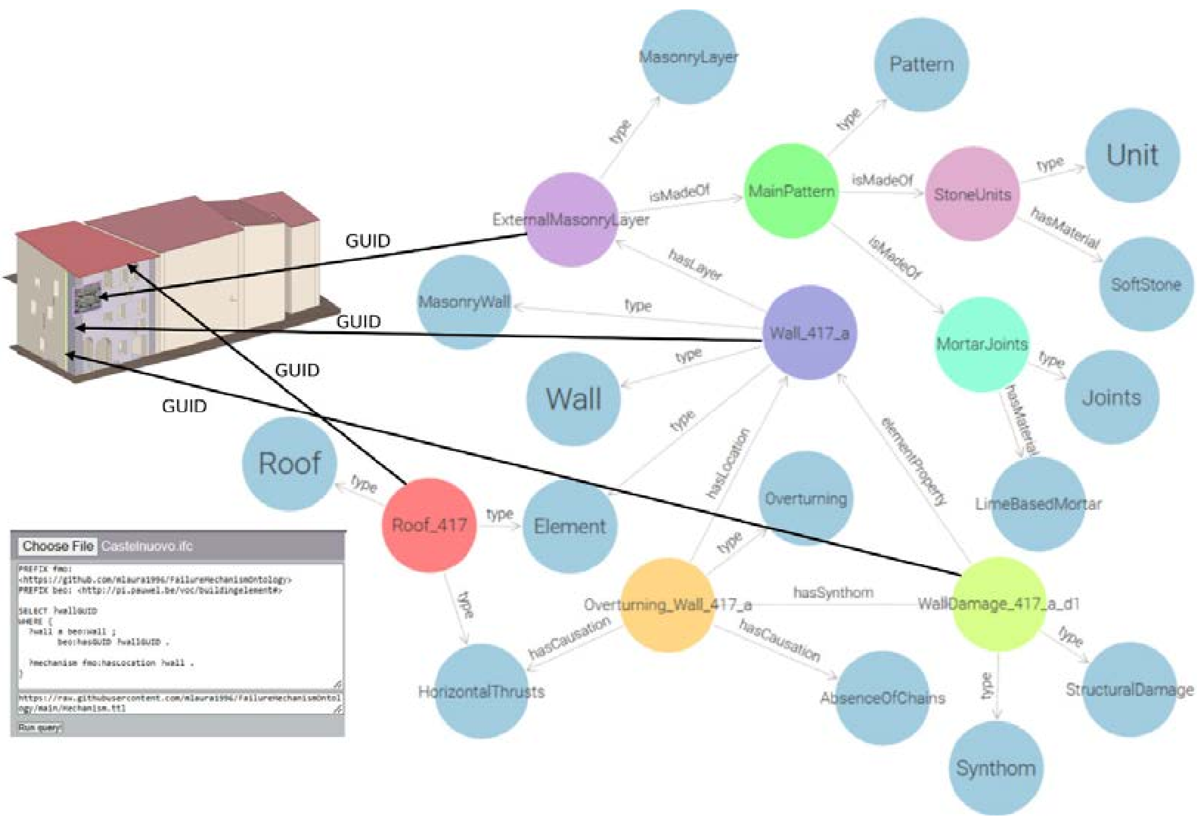

Figure 6. Mapping the IFC and the Semantic Model.

The employment of the Historic Masonry Ontology enables the modeling of diverse wall thicknesses while considering the patterns formed by units and joints. This domain ontology offers versatility and conciseness, accommodating various masonry typologies. Moreover, its seamless integration with established ontologies like BEO, MAT, and DOT enhances its utility, particularly in enriching IFC models with semantic data. Addressing the limitation of standard representations, it allows accurate association of material properties with specific masonry elements, such as bricks, stones, or mortar.

The adoption of semantic language within these ontologies results in enhanced interoperability, with the potentiality of extending into fields like chemistry and facilitating the assessment of material degradation. The possible interaction with databases presents valuable opportunities for deriving mechanical properties from data and integrating ontologies into practical applications, including inspections and monitoring processes. By integrating the Historic Masonry Ontology with the Failure Mechanism Ontology it was possible to consider, in a single semantic model, masonry characteristics and vulnerabilities. This comprehensive view allows for an objective definition of masonry quality by comparing qualitative and quantitative data.

The systematic organization of masonry quality data with other relevant wall-related information, such as near-wall damage or the presence of lateral thrusts, is another innovative aspect. These data are presented as instances of classes, incorporating a range of characteristics. For instance, the damage is described not just descriptively but also as a potential symptom of an ongoing mechanism. Similarly, the representation of the roof as a structural element and a possible pushing element further enhances the objectivity of assessments.

4. CONCLUSIONS

This contribution belongs to the field of research debating the role that digital tools assume in the activities of investigation, documentation, representation, and analysis of the built heritage. In particular, the illustrated work proposes a workflow that aims to integrate the HBIM digital environment with an ontological structure, seeking to raise the semantic level offered by current digital models for the built heritage and in particular for the analysis of building systems from a structural point of view.

In the last decade, various solutions for collecting, organizing, and managing cultural heritage information have given rise to a series of tools each with its database classification system, dedicated to representing a cultural artifact and its diverse contexts of investigation and interpretation. However, the same cannot be said of the built heritage, where on the one hand the complexity of the artifact itself and its historical evolution, and on the other hand, the presence of multiple disciplines in its processes of investigation, recovery, and intervention, have left the field effectively unexplored and lacking an organic approach to knowledge modeling. In this context, this article discusses the progressive adoption of two specific techniques - computer ontologies and the and HBIM models - highlighting their possibilities and ability to balance on the one hand the flexibility in dealing with the different disciplines involved on the other hand the rigor in information management necessary to effectively document the artifact.

The real change, therefore, is not to be found in new models for cataloging and documenting the building and its aspects but, rather, in approaches capable of integrating and making consistent the different cognitive models of the built heritage, fostering mutual understanding and collaboration among the different skills involved in such a complex process as that of investigation and documentation.

In this application, the primary focus was on the structural assessment of historic load-bearing masonry buildings. To achieve this goal, two new domain ontologies were developed, one for modeling masonry as a heterogeneous material and the other for defining vulnerabilities and related local mechanisms. This innovative contribution enables the semantic enrichment of BIM models using a Linked Data approach, effectively mapping the IFC and semantic model.

The results obtained from applying the proposed methodology allowed for the identification of its strengths and existing open issues. Among the advantages achieved, the methodology provides a more objective basis for structural assessments by considering diverse modeling assumptions. Moreover, it offers potential benefits in training new preservation experts, as the inclusive representation of the structure, materials, and preservation state fosters a better understanding of the structural behavior in existing unreinforced masonry buildings.

However, certain open issues require further development. One crucial aspect pertains to the integration of new domain ontologies into the methodology, especially for the development of global numerical models. This pioneering contribution lays the groundwork for future developments in this regard. Additionally, enhancing the user experience with the ontology is essential, and the creation of a platform that presents the ontology representation in the backend, capable of working with queries, and offering user-friendly interactions, would be highly valuable.

Furthermore, applying the proposed methodology to a larger case study with more extensive data could yield additional insights and demonstrate further benefits. Such an expanded application would reinforce the methodology's effectiveness and real-world applicability.

In conclusion, the development of the new domain ontologies and the application of the methodology present promising advancements in the field of structural assessment for historic masonry buildings. While it demonstrates numerous advantages, ongoing efforts to address open issues and explore potential enhancements will undoubtedly contribute to the continuous improvement and adoption of this innovative approach.

5. ACKNOWLEDGMENTS

We extend our gratitude to Professor Pieter Pauwels for sharing his knowledge and helping us understand the details of semantic modeling for building. His precious advice throughout this application has been invaluable to our work's success.

This work was partly financed by FCT / MCTES through national funds (PIDDAC) under the R&D Unit Institute for Sustainability and Innovation in Structural Engineering (ISISE), under reference UIDB / 04029/2020, and under the Associate Laboratory Advanced Production and Intelligent Systems ARISE under reference LA/P/0112/2020.

This work is financed by national funds through FCT - Foundation for Science and Technology, under grant agreement 2022.10204.BD attributed to the 1st author.

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VIRTUAL HUMAN-BUILDING INTERACTION EXPERIMENTATION ONTOLOGY (VHBIEO): A VHBIEO-BASED METADATA-DRIVEN EXPLORATION

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ABSTRACT: *Virtual reality (VR) offers promise as a tool for building performance simulations, especially when considering human-building interactions in buildings or spaces still under design. However, the absence of standardized data protocols impedes the consistent sharing of VR-related experiments and findings. This makes advancing VR experimentation as a reliable method for studying human-building dynamics challenging. The authors introduced the Virtual Human-Building Interaction Experimentation Ontology (VHBIEO) to address the challenge. VHBIEO seeks to standardize experimentation details as a domain-specific ontology, enhancing their interoperability. It includes essential experimentation concepts and employs semantic web technologies to ensure machine readability. Moreover, it integrates an application view (APV) to tailor details to specific experiments. Using VHBIEO-based metadata, this paper presents a case study aiming to standardize experiments that validate thermal sensations in immersive virtual environments (IVE), encompassing experimental protocol, variables, design, and data gathering. By exploring the main characteristics of VHBIEO-based metadata, the authors discuss its potential to improve the reliability of human-building interaction research.*

KEYWORDS: *Ontology, Metadata, Human-building interaction, Occupant behavior, Virtual reality, Building*

1. INTRODUCTION

Integrating virtual reality (VR) in studying human-building interactions has brought many novel opportunities to building design (Zhu et al., 2018). However, this integration is not devoid of inherent complexities. Foremost among these is the pressing requirement for rigorous standardization and systematic management of experimentation data. The present practice, characterized by non-standardized experimentation protocols, impedes researchers from optimally utilizing extant results and sharing their empirical findings efficiently. Therefore, advancing the reliability and validity of research within this domain necessitates the commitment to cultivating and adhering to the standardization of main experimentation data.

The Virtual Human-Building Interaction Experimentation Ontology (VHBIEO) was designed to standardize data pertaining to virtual human-building interaction experimentation (Chokwitthaya et al., 2023). It was developed by extending the ontology of scientific experiments (EXPO) at the domain level (Soldatova & King, 2006). The construction of VHBIEO employed the DOGMA methodology, ensuring a detailed and interconnected internal structure (Jarrar & Meersman, 2008). This ontology incorporates terms and concepts from pre-existing ontologies and semantic models and emphasizes terminologies intrinsic to virtual human-building interaction experimentation. Notably, VHBIEO possesses attributes of machine readability, accessibility, and processability. Additionally, its structure integrates Application Views (APVs), facilitating the accommodation of distinct information tailored to specific applications.

VHBIEO-based metadata thus contains the operational and application-specific information associated with VR-based experimentation. The metadata includes specific information about an experiment's components, such as the experimental protocol, design, setting, variables, and data collection procedures. The paper presents a case study showcasing the benefits of using VHBIEO-based metadata in retrieving virtual human-building interaction experimentation data. The case study specifically focuses on validating thermal sensation in an immersive virtual environment (IVE) and demonstrating how VHBIEO-based metadata can effectively capture and represent various elements of the experimental protocol, design, setting, variables, and data collection. The authors discuss how the metadata can improve the reliability of human-building interaction research by highlighting its main characteristics, including its use of the description logic, machine-readable, accessible, and processable, and inclusion of unique information through the application view (APV).

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Chanachok Chokwitthaya, Yimin Zhu, Weizhuo Lu, *Virtual Human-Building Interaction Experimentation Ontology (VHBIEO): A VHBIEO-Based Metadata-Driven Exploration,* pp. 791-800, DOI 10.36253/979-12-215-0289-3.79

2. VIRTUAL HUMAN-BUILDING INTERACTION EXPERIMENTATION ONTOLOGY (VHBIEO)

Virtual human-building interaction experimentation (VHBIEO) is an ontology developed specifically for the domain of virtual human-building interaction experimentation. It contributes to enhancing various aspects of the domain. First, it provides standardized information for VR-based experimentation, thus making information more consistent for researchers to share and reuse. Secondly, it allows for the production of machine-readable, accessible, and processable information. Finally, it aims at overcoming challenges caused by the diversity of experimental design and limitations of VR experiments. Therefore, VHBIEO can potentially accelerate the development of virtual human-building interaction experimentation as an emerging research approach. Furthermore, it can enhance collaboration between researchers, making it easier for them to share knowledge and build upon each other's work.

VHBIEO extended EXPO (Soldatova & King, 2006) and reused terms and concepts from spatial-temporal event-driven modeling (STED) (Saeidi et al., 2018), the ontology to represent energy-related occupant behavior in buildings (DNAs) (Hong et al., 2015), ifcOWL ontology (Pauwels & Terkaj, 2019), the semantic sensor network ontology (SSN) (Compton et al., 2012), the survey ontology (SUR) (Scandolari et al., 2021), and the units of measurement ontology (UO) (Gkoutos et al., 2012). The development of VHBIEO followed well-defined ontology development approaches, namely ONTOLOGIES (Uschold & Gruninger, 1996), METHONTOLOGY (Ferndndez et al., 1997), Ontology Development 101 (Noy & McGuinness, 2001), and NeOn (Suárez-Figueroa et al., 2012). It comprised three major steps: initiation, construction, and evaluation. Competency questions (CQs) were used to regulate the development process. A total of fourteen CQs represented four major requirements, which included VHBIEO must 1) provide terms describing aspects regarding virtual human-building interaction experimentation, 2) explicate its internal structure, 3) assist in the inclusion of unique information regarding particular experiments, and 4) promote machine-readable, accessible, and processable data files associated with virtual human-building interaction experimentation. VHBIEO used semantic web technologies to make it machine-readable, accessible, and processable. DOGMA methodology was applied to developing the internal structure of VHBIEO, which involves describing interconnectedness and commitment of terms, using Lexon and organizing groups of Lexons to support specific applications (Jarrar & Meersman, 2008). The commitment involves three groups, namely general, virtual, and in-situ commitments. The scheme of VHBIEO is illustrated in Fig. 1. APVs were established by adopting the concept of Model View Definition (MVD) implemented in Industry Foundation Classes (IFC) for allowing the inclusion of unique information for particular applications (Hietanen, 2006). The resources defined in VHBIEO are publicly available through a URL as https://w3id.org/vhbieo, and individual terms can be accessed using a unique URI as https://w3id.org/vhbieo#term. The ontology editor Protégé was used to support the development of VHBIEO (Musen, 2015).

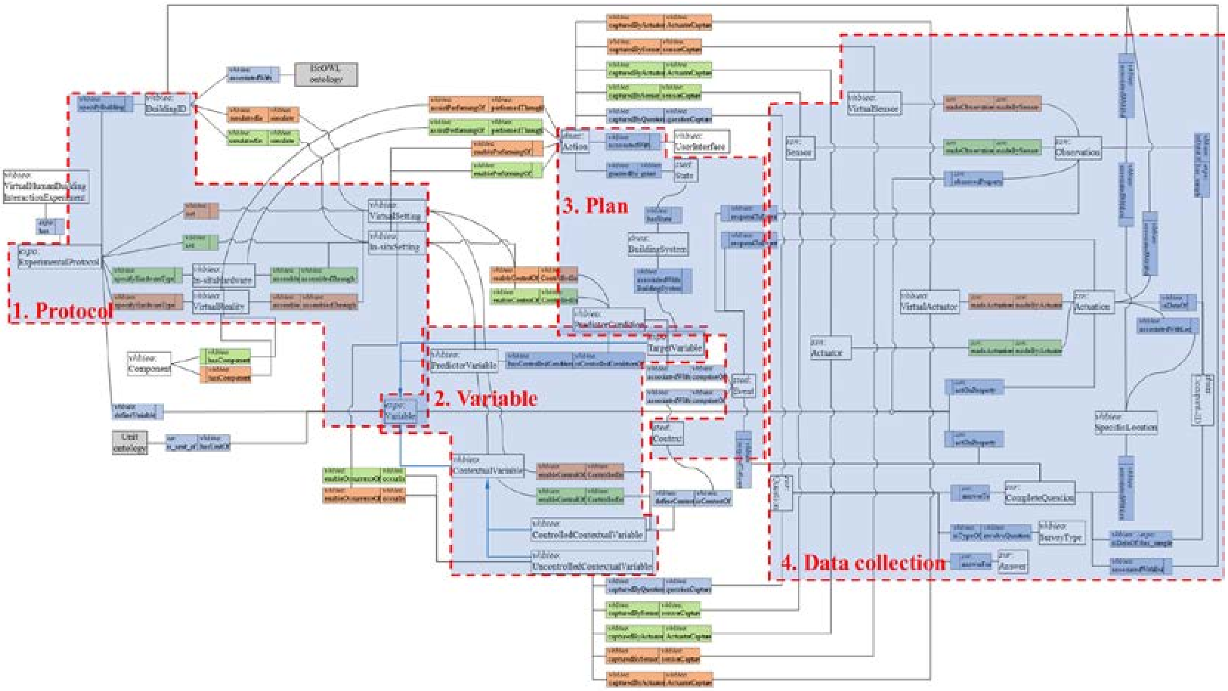

Fig. 1: Scheme of VHBIEO (Chokwitthaya et al., 2023).

The evaluation of VHBIEO was performed, consisting of two parts: taxonomy evaluation and application evaluation. The taxonomy evaluation assessed the logical sequence, the completeness of the ontology, and the redundancy of terms. It ensured that VHBIEO provided a comprehensive and coherent representation of the domain of virtual human-building interaction experimentation. The application evaluation tested the ability of VHBIEO to describe and integrate information from real-world experiments. It also showed that VHBIEO promoted machine readability, accessibility, and processibility by providing several examples of querying information in the data files. VHBIEO was able to incorporate unique information (e.g., 7-point Likert scales) using APV. The evaluation revealed the efficacy of VHBIEO in providing standardized information and enabling machine-readability, accessibility, and processability, which is crucial for promoting consistency and accelerating the maturity of the virtual human-building interaction experimentation approach.

3. CASE STUDY

The case study aims to illustrate data described in VHBIEO-based metadata and prove that the metadata was machine-readable, accessible, and processable through query using a standardized query language (SPARQL). This objective is significant because it ensures the effective utilization and interoperability of the data marked in the metadata. When metadata is machine-readable, accessible, and processable, it can be leveraged to develop sophisticated analyses and applications. The accessibility and processability of the metadata mean that it can be dynamically engaged, enabling researchers and developers to manipulate and interpret the data efficiently, enhancing the comprehensibility and utilization of the information contained within the experimentation.

The case study involves retrieving and analyzing information related to a VR-based experiment performed in an existing study (Rentala et al., 2021). The experiment primarily focused on evaluating the influence of outdoor temperature variations on participants' thermal states within IVE. It was grounded in detailed and methodical experimentation aimed at dissecting the intricacies of thermal states in varying conditions, utilizing various events to simulate diverse environmental settings. The structure of the experimental data reflected the comprehensive nature of the research and the diversity of the variables considered. The variables range from environmental conditions (e.g., indoor and outdoor temperatures and humidity) to participants' physiological (e.g., skin temperatures at various body locations and heart rate) and perceptual responses (e.g., thermal perceptions at different body locations), providing a multidimensional perspective on the impact of outdoor temperature variations on thermal states in IVE experiments. These variables provide a robust and comprehensive dataset that allows for a thorough exploration and understanding of the thermal states of participants under different environmental conditions within IVE. The comprehensive dataset allowed the creation of the VHBIEO-based metadata, exploring all commitments and the majority of Lexons and rules defined in VHBIEO. In addition, the dataset enabled the exploration of APV since the experiment included the use of 7-point Likert scales, which needed customization in VHBIEO.

The metadata was formatted in the Resource Description Framework (RDF) format, which is a standard format for representing ontologies and linked data. It was deployed on the Dataverse, a data repository platform, for testing. It was uploaded as a tabular data file that provided context and description of the data. It included information such as the experiment title, authors, funding sources, and descriptions of the data structure, variables, and observations.

3.1 VHBIEO-based metadata

The structure of VHBIEO-based metadata revolved around four core components of VHBIEO: experimental protocol, variable, plan, and data collection. This section discusses such components and their associated data pieces. The discussion aims to elucidate these components by exemplifying the key data elements pertinent to the experiment, thereby underlining the efficacy of VHBIEO in developing the metadata.

3.1.1 Experimental protocol

The experimental protocol, referred to as the backbone of the experiment, laid down the research's overarching strategy. This information was essential for understanding the core of the experiment. Fig. 2 delves into data intricately associated with the experimental protocol, illustrating several instrumental components, namely the protocol itself, experimental setting, hardware, and building, each playing a role in steering the experiment toward its intended objectives.

Within the detailed protocol (*expo*:ExperimentalProtocol), a holistic introduction and thorough description covering experimental statements, background, hypothesis, and methods sections - including inclusion and exclusion criteria - are encapsulated. Notably, the procedural roadmap for conducting the experiment, study timelines, visits, potential risks, and confidentiality assurances are also placed within this component.

The settings utilized during the experiment are distinctly described using *vhbieo*:VirtualSetting and *vhbieo*:In-situSetting, denoting the use of a fully immersive virtual environment and a climate chamber setting, respectively.

The hardware associated with these settings, integral to the execution of the experiment, is detailed through *vhbieo*:VirtualReality and *vhbieo*:In-situHardware. The critical element of a building, significantly tied to the protocol, is narrated via *vhbieo*:BuildingID. The building elements, representing architectural or design specifics, were meticulously described using the IfcOWL ontology.

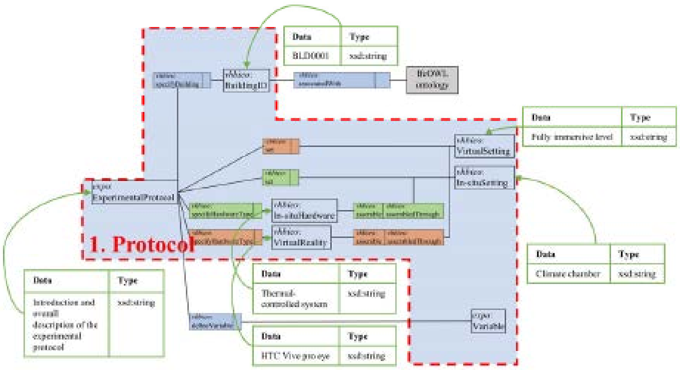

Fig. 2: Example of data associated with protocol.

3.1.2 Variable, plan, and data collection

While the concepts of variable, plan, and data collection are distinct, it is vital to recognize their interconnected nature. Variables define what data is collected, the plan dictates how to navigate and observe through the variables, and data collection strategies depict the methodology for gathering insights on these variables and aligning with the plan. Fig. 3, 4, and 5 exemplify this integrative relationship, offering a consolidated perspective through discrete examples and thereby facilitating a coherent understanding of the experiment's structure and methodology. Noteworthy is that the components spotlighted in each figure represent selective excerpts from the experiment, highlighting particular elements that significantly contribute to the focus of each example. To streamline and succinctly encapsulate the discussion, components not directly pertinent have been judiciously omitted.

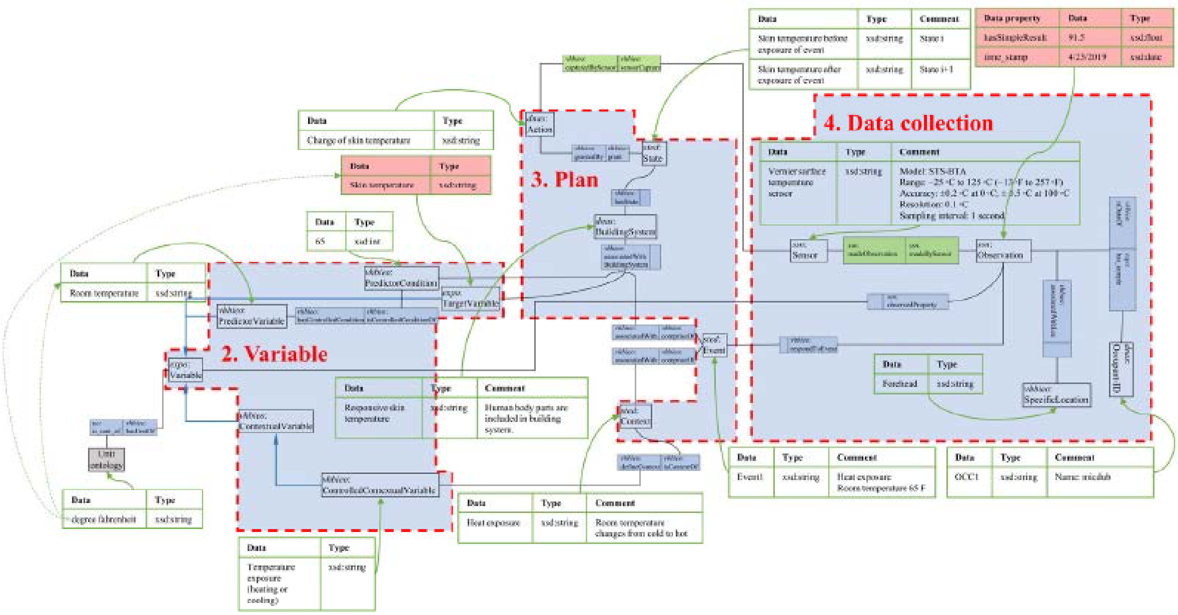

Fig. 3: Example of data associated with skin temperature.

Fig. 3 narrates variable, plan, and data collection components, specifically focusing on the human-skin temperature, particularly at the forehead. This temperature was identified as the target, or the dependent variable (*expo*:TargetVariable), for the experiment. Its measurements were taken in degrees Fahrenheit, referencing the Unit ontology. The predictor or independent variable was set as the room temperature, with a controlled setting fixed at 65 degrees Fahrenheit. This was described under *vhbieo*:PredictorVariable and *vhbieo*:PredictorCondition, respectively. The controlled contextual factor was temperature exposure (*vhbieo*:ControlledContextualVariable).

The temperature exposure outlined the context (*sted*:Context) of heat exposure as a trajectory from a cold to a hot environment. Drawing upon this setting, the predictor condition and context conjoined to devise an event (*sted*:Event) introduced to a participant in the IVE. The human body was conceptually integrated as part of the building. Consequently, the responsive skin temperature was described in the *dnas*:BuildingSystem, linking it directly to the target variable of skin temperature. Invoking the concept of "state" from STED (as elaborated by Saeidi et al., 2018), a state embodies the dynamic status of the building system. It is susceptible to variations stemming from occupants' interactions and responses to the events they are subjected to. As a result, the skin temperature responses manifested in multiple states, including the temperature recordings before and after event exposure (*sted*:State). These recordings translated into the very act of skin temperature alterations encapsulated under *dnas*:Action.

To hone in on data collection specifics, Fig. 3 illustrates using the Vernier surface temperature sensor under *ssn*:Sensor. This sensor was strategically positioned on the forehead described under *vhbieo*:SpecificLocation of the participant, uniquely identified by *dnas*:Occupant-ID. The resulting data was systematically chronicled in *ssn*:Observation. It showed a recorded forehead skin temperature of 91.5 degrees Fahrenheit, timestamped precisely to mark the experiment's execution on 23rd April 2019.

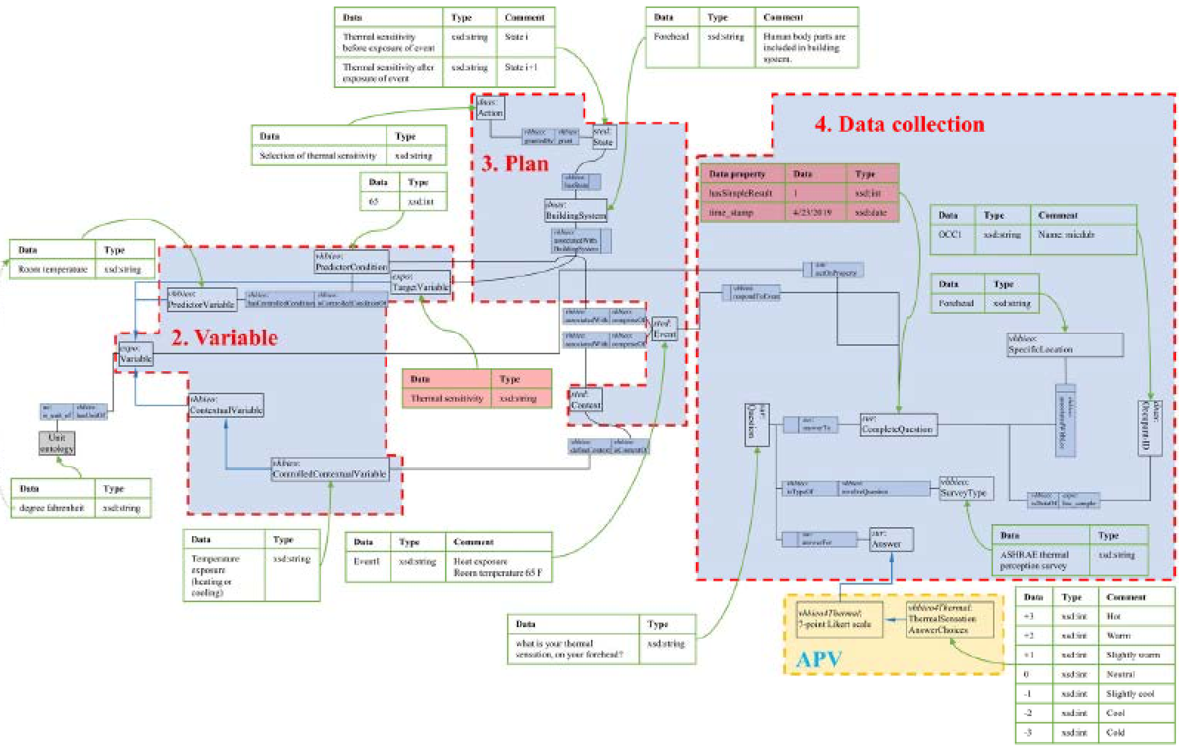

Fig. 4: Example of data associated with thermal sensation.

Fig. 4 provides a detailed examination of the variable, plan, and data collection components with a concentration on thermal sensation—another distinct target variable within the experiment. The structures of the variable and plan components mirrored those elaborated upon in Fig. 3. However, the method of data collection exhibited notable differences.

In the context of thermal sensation, data was accumulated through a survey mechanism, described in *sur*:Question. Significantly, the application view (APV) was utilized to annotate and clarify the 7-point Likert scale, which constituted the unique response choices in the experiment. This scale was referenced as (*vhbieo4Thermal*:ThermalSensationAnswerChoices). The nature of this question aligned with a thermal perception survey, a standard defined and endorsed by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) and cataloged under (*vhbieo*:SurveyType). The culmination of this survey's execution was preserved under *sur*:CompleteQuestion, which depicted the participant's thermal sensation as being "slightly warm". It was anchored with a timestamp, noting the date of conducting the experiment.

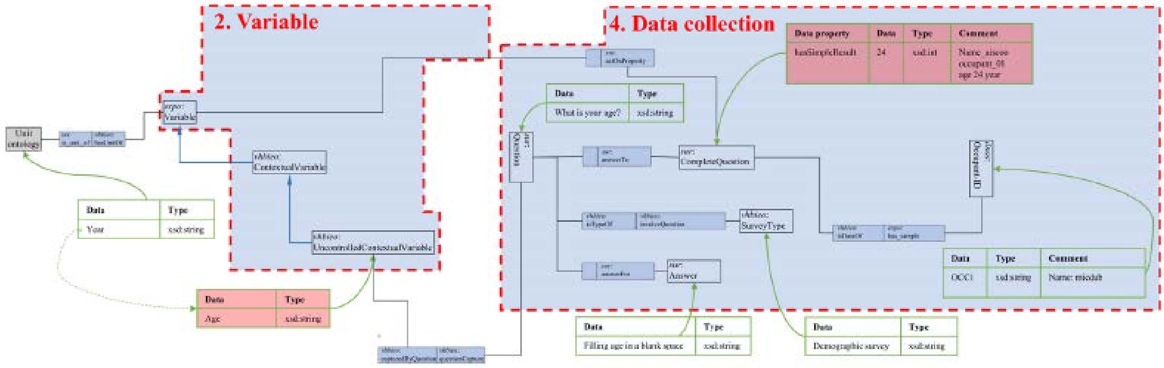

Fig. 5: Example of data associated with age.

Fig. 5 shifts its focus from target variables and delves into an uncontrolled contextual variable encountered in the experiment—specifically, the age (*vhbieo*:UncontrolledContextualVariable) of a participant. The unit used to measure age was "year", which draws reference from the Unit ontology. For data collection pertaining to age, a demographic survey (*vhbieo*:SurveyType) was employed. Participants were prompted with a straightforward question, "What is your age?", which was recorded under *sur*:Question. Responding to this question required participants to fill in a blank space, indicating their age, and this form of response was described in *sur*:Answer. In a manner akin to the thermal sensation data collection, the resultant age data was encapsulated under *sur*:CompleteQuestion. This documented an instance of a participant's age being 24 years old.

3.2 Querying VHBIEO-Based Metadata

The executed data query was instrumental in validating the machine-readability, accessibility, and processability of the metadata. To resonate with the provided examples, the query was formulated to extract specific data points corresponding to variables such as the skin temperature at the forehead, thermal sensation, and age. In conjunction, the computation of averages for each variable within the query further attested to the metadata's machine-processable nature. This ability to programmatically access, read, and compute values from the metadata substantiates its utility and robustness in supporting research and data-driven applications.

Fig. 6 presents the specific queries crafted to extract data pertaining to the skin temperature (Fig. 6a), thermal sensation (Fig. 6b), and age (Fig. 6c) of all participants. These queries are structured to target the data points within the dataset precisely. It also conveys the outcome of the queries. Notably, the result encapsulated the computed averages of the obtained data, underlining the machine-processable nature of the metadata.

For Fig. 6a, the query primarily focuses on obtaining data related to the forehead skin temperature of participants. Such data held significant relevance, as skin temperature could provide insights into a participant's thermoregulation response in a given environment. By furnishing both individual temperature data points and an overall average, the query aided researchers in discerning patterns and anomalies within the data.

The emphasis in Fig. 6b shifts from physiological responses to perceptual experiences. Querying the thermal sensation looked into how participants subjectively felt about the thermal environment they were placed in. The provision of an average sensation value offered a summarised perspective. Such data could be vital in studies aiming to align objective environmental parameters with subjective human comfort levels.

The query in Fig. 6c acknowledges the demographic diversity of the participants. Age is a potential confounding variable in many human studies, as age might influence a person's physiological or perceptual response to environmental factors. Researchers could factor in age-related nuances in their analysis by procuring both individual age data and its average.

In essence, these queries demonstrate the versatility and depth of VHBIEO-based metadata. Furthermore, the structure of each query, particularly the incorporation of averages, emphasizes granularity and summarization, ensuring that the metadata is machine-readable, accessible, and processible.

```
PREFIX expo: <http://www.hozo.jp/owl/EXPOApr19/>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-systax-ns#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX sosa: <http://www.w3.org/ns/sosa/>
PREFIX vhbieo: <https://w3id.org/vhbieo#>
SELECT ?occupantID ?property ?temperature ?location ?Average_forehead_temperature
    WHERE {
    {
        SELECT (AVG(?Result) AS ?Average_forehead_temperature) ("" AS ?occupantID)
        ("" AS ?property) ("" AS ?temperature) ("" AS ?location) ("" AS ?Result)
        WHERE {
            ?individual a sosa:Observation .
            ?individual ?property_ ?value_ .
            FILTER (?value_ = vhbieo:HBL000002)
            ?individual sosa:hasSimpleResult ?Result .
        }
    }
    UNION
    {
        ?occupantID a sosa:Observation .
        ?occupantID ?property_ ?value_ .
        FILTER (?value_ = vhbieo:HBL000002)

        OPTIONAL {?value_ rdfs:comment ?location }
        ?occupantID ?property ?temperature .
        FILTER (?property = sosa:hasSimpleResult)
        BIND("" AS ?Average_forehead_temperature)
    }}
    ORDER BY ASC(?Average_forehead_temperature)
```

OccupantID	Property	Temperature	Location	Average forehead temperature
				91.22
OCC0001	hasSimpleResult	91.57	forehead	
OCC0002	hasSimpleResult	93.00	forehead	
OCC0003	hasSimpleResult	94.38	forehead	
OCC0004	hasSimpleResult	92.80	forehead	
OCC0005	hasSimpleResult	95.84	forehead	
OCC0006	hasSimpleResult	97.11	forehead	
...	...	...	...	

(a) Skin temperature at forehead.

```
PREFIX expo: <http://www.hozo.jp/owl/EXPOApr19/>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-systax-ns#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX sosa: <http://www.w3.org/ns/sosa/>
PREFIX vhbieo: <https://w3id.org/vhbieo#>
SELECT ?occupantID ?property ?temperature ?location ?Average_forehead_sensation
    WHERE {
    {
        SELECT (AVG(?Result) AS ?Average_forehead_sensation) ("" AS ?occupantID)
        ("" AS ?property) ("" AS ?sensation) ("" AS ?location) ("" AS ?Result)
        WHERE {
            ?individual a sur:CompleteQuestion .
            ?individual ?property_ ?value_ .
            FILTER (?value_ = vhbieo:TAV000006)
            ?individual sosa:hasSimpleResult ?Result .
        }
    }
    UNION
    {
        ?occupantID a sur:CompleteQuestion .
        ?occupantID ?property_ ?value_ .
        FILTER (?value_ = vhbieo:TAV000006)

        OPTIONAL {?value_ rdfs:comment ?location }
        ?occupantID ?property ?sensation .
        FILTER (?property = sosa:hasSimpleResult)
        BIND("" AS ?Average_forehead_sensation)
    }}
    ORDER BY ASC(?Average_forehead_sensation)
```

OccupantID	Property	Thermal sensation	Location	Average forehead thermal sensation
				0.62
OCC0001	hasSimpleResult	-2	forehead	
OCC0002	hasSimpleResult	1	forehead	
OCC0003	hasSimpleResult	0	forehead	
OCC0004	hasSimpleResult	0	forehead	
OCC0005	hasSimpleResult	-1	forehead	
OCC0006	hasSimpleResult	-1	forehead	
...	...	...	...	

(b) Thermal sensation at forehead.

```
PREFIX expo: <http://www.hozo.jp/owl/EXPOApr19/>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-systax-ns#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX sosa: <http://www.w3.org/ns/sosa/>
PREFIX vhbieo: <https://w3id.org/vhbieo#>
SELECT ?occupantID ?property ?age ?Average_age
    WHERE {
    {
        SELECT (AVG(?Result) AS ?Average_age) ("" AS ?occupantID)
        ("" AS ?property) ("" AS ?age) ("" AS ?Result)
        WHERE {
            ?individual a sur:CompleteQuestion .
            ?individual ?property_ ?value_ .
            FILTER (?value_ = vhbieo:UCV000003)
            ?individual sosa:hasSimpleResult ?Result .
        }
    }
    UNION
    {
        ?occupantID a sur:CompleteQuestion .
        ?occupantID ?property_ ?value_ .
        FILTER (?value_ = vhbieo:UCV000003)
        ?occupantID ?property ?age .
        FILTER (?property = sosa:hasSimpleResult)
        BIND("" AS ?Average_age)
    }}
    ORDER BY ASC(?Average_age)
```

OccupantID	Property	Age	Location	Average age
				25.71
OCC0001	hasSimpleResult	24	forehead	
OCC0002	hasSimpleResult	26	forehead	
OCC0003	hasSimpleResult	21	forehead	
OCC0004	hasSimpleResult	35	forehead	
OCC0005	hasSimpleResult	42	forehead	
OCC0006	hasSimpleResult	32	forehead	
...	...	...	...	

(c) Age of participants.

Fig. 6: Queries and their results.

4. DISCUSSION

The primary objective of this work was to demonstrate the efficacy of the Virtual Human-Building Interaction Experimentation Ontology (VHBIEO) in supporting the development of VHBIEO-based metadata. This metadata aims to create a structured representation of experimental data, promoting machine-readability, accessibility, and processability. Reflecting upon the objective, development of VHBIEO-based metadata, and query results, this section broke down the accomplishments, implications, and broader impact on the research horizon.

Systematic Representation: At its core, VHBIEO is an ontology that aims to systematically represent knowledge in the domain of human-building interaction experiments. The VHBIEO-based metadata took advantage of this structured knowledge representation, ensuring that every aspect of an experiment was adequately documented, from the broader experimental protocol to the minutiae of data collection methodologies.

Data Accessibility and Processability: The design of VHBIEO ensures that data is machine-readable, accessible, and processible. This was evident in the queries we discussed (e.g., Fig. 6), which retrieved data efficiently and could also compute statistics such as averages, showcasing the power and flexibility of this ontology-based metadata.

Facilitating Advanced Analyses: The granularity offered by the VHBIEO-based metadata, segmenting data into categories like skin temperature, thermal sensation, and age, paved the way for more complex and nuanced analyses. Discerning patterns or influences among these variables became relatively straightforward when they were clearly organized.

Overall, VHBIEO provides standardization for virtual human-building interaction experimentation as a robust mechanism for associated experimental data. Such standardization diminishes the scope of ambiguities, ensuring the data remains consistent across different stages and platforms of its utilization. Furthermore, data exchange across diverse platforms and researchers is inevitable. VHBIEO potentially enables researchers to transfer, match, and integrate data from varied sources without the nuances of interpretation. This is akin to creating a seamless bridge where data flows without errors.

5. LIMITATION

Despite the evident advantages and the transformative potential of VHBIEO, certain limitations need to be considered.

Continuous Maintenance and Refinement: A pressing challenge associated with ontologies, VHBIEO being no exception, is their continuous upkeep. Changes in domain knowledge or enhancements in ontology capabilities require periodic revisions. This process demands not just a technological revamp but also the infusion of domain-specific expertise to ensure the ontology stays relevant and accurate.

Potential Overlaps with Existing Ontologies: It is conceivable that some terms introduced in VHBIEO might overlap with those in existing ontologies or semantic models. The authors, in their initial sweep, might not have identified these overlaps. Should such duplications be spotted in the future, VHBIEO will be updated to reflect a more harmonized structure.

Scalability with Evolving VR Technology: Virtual Reality (VR) technologies are in a state of flux, constantly evolving. As VR matures, simulating intricate simulations over prolonged durations might become feasible. In such scenarios, the foundational structure of VHBIEO, anchored on STED, might demand reevaluation and fine-tuning.

Potential Limitations in Collaborative Experiments: As research becomes increasingly collaborative, the experiments often span multiple geographies and phases. This dynamic nature of collaboration, marked by continuous data exchanges and iterative updates, could pose challenges for VHBIEO in its current form. Future iterations of VHBIEO will need to address this aspect to stay relevant in an interconnected research ecosystem.

Lack of Advanced Features in APV: Although the current APV supports unique terminology descriptions tailored for specific experiments, it falls short in several other features. Features such as internal structure customization, automation capabilities, and bridging with other ontologies are crucial for enriching VHBIEO's utility. The integration of these features could significantly expand its scope and application.

6. CONCLUSION

The study showcased the advantages of using VHBIEO in human-building interaction research. By providing a structured approach to document experimental protocol, design, settings, variables, and data collection, VHBIEO-based metadata paves the way for better experiment reusability, comparability, and reproducibility. This is especially crucial for experiments relying on IVE-based experimental information and results. Yet, it is crucial to acknowledge the limitations inherent in this preliminary implementation. Specifically, the research's scope was constrained mainly due to the limited number of validation cases. As the field progresses, it is essential to continually refine VHBIEO by addressing these limitations and validating its utility across a broader array of experimental contexts.

7. ACKNOWLEDGEMENT

This study is based upon work supported by the National Science Foundation, the United States, under grant No. 1805914 and grant No. 1640818, and the Kempestiftelserna under grant No. JCK-2136. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation and the Kempestiftelserna Foundation.

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CONSISTENCY VERIFICATION BETWEEN COST AND GEOMETRIC INFORMATION BASED ON IFC: APPLICATION ON STRUCTURAL ELEMENTS

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ABSTRACT: *Cost estimation for tendering is one of the leading causes of legal disputes in the architecture, engineering, construction, and facilities management (AEC/FM) industry.*

The lack of a standardised support procedure to verify the association of cost data with the objects model causes waste of time and inaccuracy in the cost estimation.

This research work, starting from a previous study where the research group integrated a cost domain in the IFC data schema, investigated the possible applications of this IFC based cost domain integrated with an IFC geometrical information model. The current paper investigates a specific case study focused on a structural model to verify current and future applications.

Furthermore, rules for BIM information requirements will be defined through the Information Delivery Specification (IDS) to ensure an easy way for humans and computers to understand it. This will allow to specify which data must be present in the geometric model to subsequently ensure validation and verification of uniqueness of the cost data associated with geometric data.

The results show the possibility to define a structured cost items in IFC associated through relationships to other entities and then verify their association to geometric data to guarantee its consistency and uniqueness.

KEYWORDS: *IFC, cost ontology, BIM, cost item, Information Delivery Specification (IDS)*

1. INTRODUCTION

Cost estimation is one of the most critical tasks and still unresolved problem in the architecture, engineering, construction, and facilities management (AEC/FM) industry.

To be able to obtain a cost estimate for a building, it is generally necessary to classify all objects in the building project using articles and to record their quantities. Although this is an objective process, human errors can often be encountered relating to both the incorrect association of prices and the incorrect calculation of quantities. One of the problems facing the AEC industry today is precisely the lack of a standardised support procedure to verify the association of cost data (Adeli et al., 2001; Lu et al., 2016). With the advent of BIM, computing tools have changed and evolved digitally. Wu et al., (2014), Sacks et al., (2018), Elghaish et al., (2020), and Olatunji et al., (2021) reported on the possibilities of BIM to improve and support cost estimation, but the approach to computing has remained the same. So, the problem remains; in fact, while previously the costs were associated with measurements, they are now associated with model objects but there is no certainty that this association is correct and consistent.

Currently the computation software receives the information from a model exported in an open format, Industry Foundation Classes (IFC) and retains the cost listing within it. With this study, the aim is to compensate for the lack of standardisation in cost validation by creating an IFC-based cost semantics, thus identifying a common language between model objects and costs.

The IFC is standardized according to ISO 16739-1. This could provide a solid basis for the exchange of information resources between information systems (Froese T et al., 1999). The IFC standard published by Buildingsmart International plays a very important role in the process of exchanging BIM data between the various participants in a building construction or management project, as it is an open specification. IFC provides some entities to represent information in building management, including *IfcConstructionManagementResource* (building resource) *IfcWorkPlan* (planning), *IfcTask* (task), *IfcScheduleuleTimeControl* (task time information),

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)

IfcCostSchedule (cost planning), *IfcCostItem* (unit cost estimation item) and *IfcCostValue* (value).

This research work, starting from a previous study in which the research team integrated a cost domain into the IFC data model (Cassandro et al., 2023), investigates the possible development of a standardised support procedure to verify the uniqueness and correctness of the association between the new cost items and their written information within the IFC standard and the geometric objects contained in a specific case study, a structural model.

Currently, in Italy, the cost items are contained in the list of public works (in the specific case of the Price List of the Lombardy Region) a document based on unstructured data and characterized by a natural language.

Starting from a work previously developed by the research team (Cassandro et al., 2023), it was possible to initially create an IDS file for the definition of the requirements that must be present in the geometric model. This is fundamental to guarantee both the correct association of the entities of cost but also the analysis and the interrogation of the data in the successive phases of verification. Subsequently it is possible to verify the association between the cost items and the geometric objects to ensure the uniqueness and correctness of the cost-object relationships created.

Specifically, this would allow to:

- check the correct price association;
- ensure validation, uniqueness and comparison between attributes of a certain cost class and the attributes of the object to which it is associated;
- consider cost elements as standardizable and query-able computer classes.

The example of a structural model has been taken and a structure of relations between costs and geometry has been created to allow the verification of the uniqueness of associated data and validate the code developed.

The paper is structured as follows. First an analysis of the existing literature on cost estimation via IFC classes, current methods of checking compliance and the Information Delivery Specification standard (IDS) is presented. Currently there are not BIM authoring software that can write the *IfcCostItem* entity and as a result you cannot check this information; so, it was decided to rely on the IfcOpenShell library to initially create the cost items and then verify the association and accuracy of the data of the entity through the code developed for this research.

2. THEORETICAL BACKGROUND

Within the BIM process, one of the most relevant parts is undoubtedly the validation of the model and the information it contains for a proper exchange of data. There may currently be different types of project's validation, or model checking, and they may be the following:

- verification against geometry (clash detection);
- verification against design settings (e.g. the specifications within the BEP, BIM validation);
- checks against regulations (code checking)

The purpose of these checks is to ensure that all data entered within the model is correct from a geometric and informative point of view, and that it meets all standards.

Currently, this check is a process that, while being facilitated using software and tools, still remains time-consuming, expensive and prone to errors (Dimyadi & Amor, 2013). The main problem of model checking always concerns the validation process (Ghannad et al., 2019).

2.1 Model Checking

Model checking is a key element in information modeling and management (Ciribini et al., 2015). In standard design processes, according to studies, only 5-10% of the information content of the project is systematically checked (Trebbi et al., 2020).

Clash detection means the verification of geometric interference; this could become a problem during the construction of the work which is not checked in advance within the 3D model (Akponeware & Adamu, 2017). These are divided into two types; the "hard clash" referred to two objects that collide and occupy the same physical space, and the "soft clash" referred to objects that do not collide but are too close.

Code checking is the verification of the compliance of the digital model with the corresponding regulation (Trebbi et al., 2020). The use of specific software that supports these controls can reduce time and error, thereby improving several aspects of building design, including efficiency and model quality (Greenwood et al., 2010).

It is essential to verify the compliance of the models with regulatory and technical requirements, and therefore an automatic control of the frequency and uniqueness of the information would have a significant value within the AEC industry (Solihin & Eastman, 2015). Furthermore, it may be necessary to verify compliance with the requirements of "Employer Information Requirements" (E.I.R.) or of "BIM Execution Plan" (B.E.P.) (PAS 1192-2:2013).

The first study on automated code compliance checking is the Singapore project CORENET (Construction and Real Estate Network) an initiative based on the complete integration of the life cycle phases. Similarly, in the USA SMARTCodes was born and Autodesk Revit provided some plug-ins such as UpCodesAI which supports some parts of the International Building Code but also some parts of other standards from other jurisdictions, in Australia DesignCheck.

2.2 Existing Applications

Model checking is normally done by use of standalone applications as Solibri Model Checker, SMARTcodes, ePlanCheck, AEC3 Compliance or EDM Model Server (Ismail et al., 2023). An often used example of model checking is clash detection to validate if for example different types of pipes intersect each other. Another example can be to check if the width of the doors is according to codes of accessibility in the regulations or national standards. The most used for model data verification are Solibri Model Checker and Naviswork.

Solibri Model Checker (SMC) is a prominent BIM software application which assist designers in visualizing any issues or problems regarding the design model before and during construction. It is one of the few software packages that leaves the end user with a minimum of scope for action. The rules set in SMC are set for the Norwegian State Administrative Agency handbook but can be modified by the end user by changing the rule set or deleting some. The creation of new rules is possible but has limitations. To be able to create new rules, it is necessary to act on the API, which is not public.

Naviswork, is one of the most widely used tools on clash detection and coordination of models from different disciplines. The software detects intersections or conflicts between elements in the 3D model, helping to identify and resolve construction or design issues promptly, reducing errors and costs during project execution.

3. PROBLEM STATEMENT

As can be seen from the literature analysis above, typically the verification is done within the geometric model considering only one domain (that of the model itself). Instead, the goal of the research is to validate data between a plurality of domains linked together (in this case the geometric domain and the cost domain) and that can be contained in the same model. The architectures of cost items cannot be considered exclusively as strings of text in natural language because they are not machines readable. For this reason, to verify and validate the consistency and uniqueness of the data, it is necessary to structure according to a semantic defined cost items in more complex architectures thus creating a cost domain. This should ensure that the consistency of associated data between cost and geometry can be verified.

Starting from this statement, the research focuses on the key aspect of:

- How to define a procedure for checking and verifying data between geometric and cost domains.

4. RESEARCH AIM & METHODOLOGY

This research investigates the development of a standardized support procedure to verify the correspondence between the cost items and the data they contain with the objects contained in the information models.

The cost data in this research are stored in a new cost database based on architectures developed in openBIM format and structured according to the IFC data model (Cassandro et al., 2023); currently, in Italy and in the specific case of the list of public works of the Lombardy Region, cost items are present in unstructured format within textual documents in natural language. This causes problems and possible errors both in the association and in the verification of the associated costs. In fact, currently one of the most challenging issues for building design compliance checking is the translation of human-readable rules/documents into a computer processable code to allow the understanding also by computer tools.

For this work a specific case study focused on a structural model containing cost items, structured and in IFC format, already associated with their geometric objects, is analazyed to verify the current and future applications of this methodology.

Furthermore, rules for BIM information requirements are defined through the Information Delivery Specification (IDS) to ensure an easy way for humans and computers to understand it. This allows you to define which data must be present in the geometric model to ensure first a correct cost association and later validation and verification of the uniqueness of the cost data associated with geometric data.

First, it is described the state of the art of current practices and research related to compliance checking. The idea is to standardize cost element data as a structured class in the IFC data model. This in fact contains a set of attributes that allow cost data to be stored, as is already the case for model objects.

A simple unit cost database has been created (the new digitised price list) based on IFC files relating to cost items of structural works (concrete casting, reinforcement laying, formwork laying, etc.). These files can be called in any geometric model for the definition of the cost to associate to the objects of the model.

The next step is characterized by the definition of the requirements that must be present in the geometric model for a better and correct association between IFC entities, *IfcCostItem* and *IfcElement*.

It is defined the Information Delivery Specification (IDS) that will be delivered to the modeler and after that a code is developed that will allow to verify if the association of the cost is coherent or not with the object identified.

The entity will allow to translate the current cost items, in natural language, in a defined and standardized data structure (definition of the framework and the semantics of the costs through the entity *IfcCostItem*).

The methodology adopted is characterized by the steps presented in Figure 1.

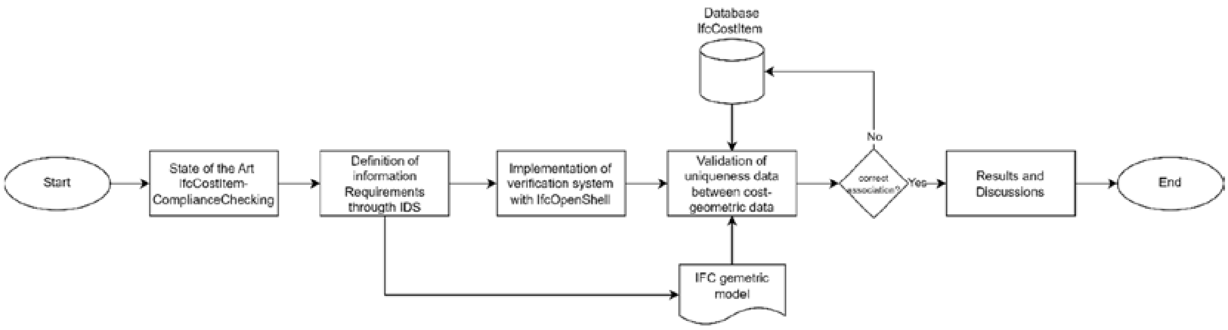


Fig. 1: Research Methodology

5. KEY CONCEPT

The IFC, an open and interoperable standard, aims to "allow interoperability between industrial processes of all different professional sectors in civil engineering projects by allowing IT applications used by all project participants to share and exchange information about the project" (BuildingSMART, 2023). It is an open international standard, standardized according to ISO 16739-1:2018; it is designed to be a vendor-independent data model and usable in a wide range of hardware devices, software platforms and interfaces for many different use cases.

5.1 IfcCostItem

IfcCostItem is a non-geometric entity, subclass of *IfcControl*, within IFC. *IfcCostItem* describes a cost or financial value with descriptive information that describes its context (BuildingSMART, 2022). It represents the cost of assets and services, the execution of works by a process, lifecycle cost, cost estimates, budgets, and more.

IfcCostItem is also described through a set of attributes. Some of them are inherited instead the attributes PredefinedType, CostQuantites and CostValue are those owners of the class. An *IfcCostItem* can link one or many

IfcCostValue's representing a unit cost, total cost, or a unit cost with one or many quantities used to generate the total cost. The quantities can be given as individual quantities, or those quantities are provided as element quantities by one or many building elements. Another key aspect is that *IfcCostItem* can activate some different relationship. Among these it can be nested to create cost assemblies through the relation *IfcRelNests*, it can be assigned to a *IfcProduct* through the relation *IfcRelAssignsToControl* but may also have a product associated through the relation *IfcRelAssignsToProduct* or a resource through the relation *IfcRelAssignsToResource*.

5.2 Information Delivery Specification

The Information Delivery Specification (IDS) is a standard defined by BuildingSMART to define the required level of information in the specific project (BuildingSMART, 2023). IDS defines the information requirements that a geometric model must contain for the correct exchange of data in a way that is easily readable by humans and interpretable by the machine. It defines how to deliver and exchange objects, property, even values and units of measurement. An IDS file may contain several requirements independent of each other and without reference to other requirements in the file. This allows you to create replicable blocks and use them in different files.

Currently the information requirements are shared through excel sheets or PDFs; these are not directly interpretable by a machine and difficult to read by people given the large amount of data.

The IDS focuses on 'information delivery specifications' defining what information is needed and how it should be structured. This should improve automated workflows by receiving information that can be processed automatically. The definition of an IDS also serves to standardize all the different approaches that there may be in modelling. An example of different approaches may be the use of slabs instead of landings.

6. EXPERIMENTATION & RESULTS

In this article, part of a larger research work carried out by this research group, the uniqueness and correctness of the association of cost items with geometric objects has been analysed and validated. This has been achieved by defining a standardized data structure translated within the IFC standard, as cost data is in natural language (unstructured data). This allows you to define a database of cost data within the IFC standard through the classes currently present (*IfcCostItem*, *IfcCostValue*, etc.) and the relationships that these can activate.

The current paper investigates a specific case study focused on a structural model.

Not being the objective of the article and having been analysed in (Cassandro et al., 2023), it will not be explained as it has been defined the structure and the relations of the single item of cost inside the standard IFC and as this is related to the geometric entity. Figure 2 shows a simplified example of the possible architecture behind the cost item related to the concrete casting for a foundation; this item like all the others will be stored in the new database of cost items.

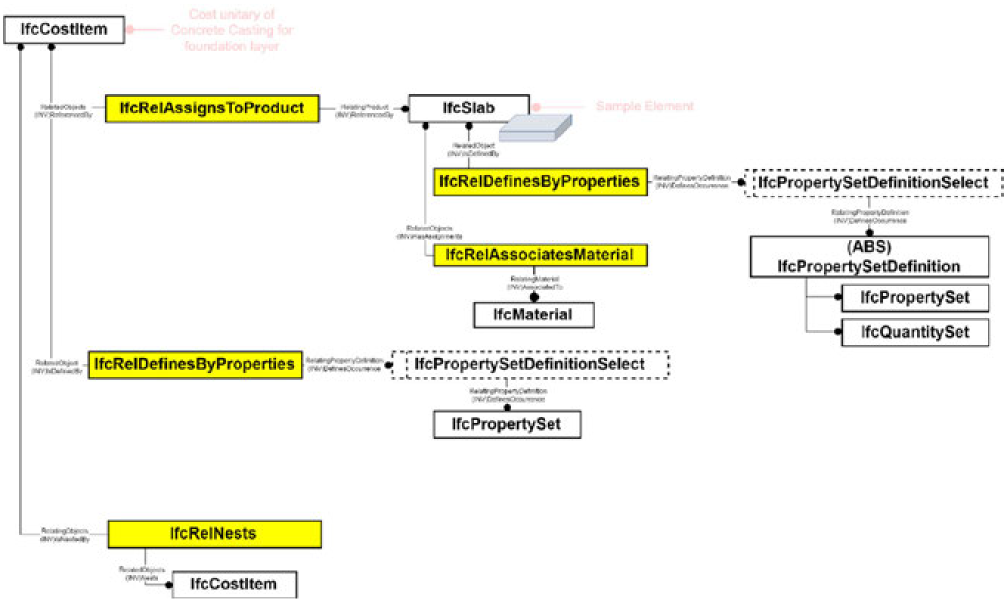


Fig. 2: Simplified example of architecture behind the cost item related to the concrete casting for a foundation.

All data used and related to cost items come from the price list of the Lombardy Region. In Italy the estimation of the prices in public tendering takes place using a price list. Each region has a catalogue containing price items, called price list, which is the basis of the economic offer and regulates payments in public contracts.

6.1 Model Requirements

Starting from a detailed analysis of the cost items, the minimum requirements (Level Of Information Need) that the geometric model must contain to ensure the subsequent association, verification and validation of data between geometric objects and cost items have been identified. It was possible to define the basic requirements to be delivered to the modeler on the basis of a work of analysis and breakdown of the current cost items for the identification of a new standardized architecture in which to insert and structure the current cost items.

The information that a single geometric entity must have in the model (called Facet in the standard IDS) have been defined. In the first part of the facet (applicability section), it was defined to which type of objects the specification applies and then it was defined the requirements (requirements section) that is required for the objects specified in the first part, such as required properties or classifications. Each specification has metadata (name, description, or instructions) to help describe the goals and instructions of how to achieve it before the applicability section (Figure 3, Figure 4). In the following example we ask as fundamental requisites that all *IfcSlab* entities of the geometric model (applicability) have compiled both the attribute "PredefinedType" according to the specific values defined by the standard (only these values are accepted: BASESLAB, FLOOR, LANDING, ROOF, NOTDEFINED, USERDEFINED) and the attribute "Name" with unspecified value (requirements).

THE ENTITY IFCSLAB MUST HAVE NAME AND PREDEFINEDTYPE

APPLIES TO:

ALL *SLAB* DATA

REQUIREMENTS:

SHAL BE *SLAB* DATA WITH A TYPE OF EITHER BASESLAB OR FLOOR OR LANDING OR ROOF OR NOTDEFINED OR USERDEFINED

THE *NAME* SHALL BE PROVIDED

Fig. 3: Simplified IDS user visualization with "IfcTester" web application.

```
<ids:specification ifcVersion="IFC4" name="The entity IfcSlab must have Name and PredefinedType" minOccurs="0" maxOccurs="unbounded">
    <ids:applicability>
        <ids:entity>
            <ids:name>
                <ids:simpleValue>IFCSLAB</ids:simpleValue>
            </ids:name>
        </ids:entity>
    </ids:applicability>
    <ids:requirements>
        <ids:entity>
            <ids:name>
                <ids:simpleValue>IFCSLAB</ids:simpleValue>
            </ids:name>
            <ids:predefinedType>
                <xs:restriction base="xs:string">
                    <xs:enumeration value="BASESLAB" />
                    <xs:enumeration value="FLOOR" />
                    <xs:enumeration value="LANDING" />
                    <xs:enumeration value="ROOF" />
                    <xs:enumeration value="NOTDEFINED" />
                    <xs:enumeration value="USERDEFINED" />
                </xs:restriction>
            </ids:predefinedType>
        </ids:entity>
        <ids:attribute minOccurs="1" maxOccurs="1">
            <ids:name>
                <ids:simpleValue>name</ids:simpleValue>
            </ids:name>
        </ids:attribute>
    </ids:requirements>
</ids:specification>
```

Fig. 4: IDS document in machine-readable xml format.

The rules for the BIM information requirements that have been defined have been collected in Table 1. Two examples of requirements for modeling structural and non-structural foundations are given. We can see how the "Req.1" defines the requirements that each individual object of the model exported as *IfcSlab*.BASESLAB with Loadbearing value false (applicability) must have.

The ACCA software "usBIM.IDS" was used to verify the requirements and the correctness of the geometric model. It was therefore possible to verify the information contained in the geometric model and to detect discrepancies from the requirements initially defined and necessary.

Table 1: Examples of requirements for modeling structural and non-structural foundations

	Applicability	Requirements		
Requirement 1	*IfcSlab*.BASESLAB	Attribute	Name	-
	Loadbearing FALSE	Pset_ConcreteElementGeneral	ConstructionMethod	In Situ
			StrengthClass	C16/20
			ExposureClass	X0
			StructuralClass	S4
		Pset_SlabCommon	FireRating	-
			IsExternal	-
			LoadBearing	FALSE
			Status	NEW
		Qto_SlabBaseQuantities	Depth	-
			Width	-
			Length	-
			Perimeter	-
			GrossVolume	-
			NetVolume	-
Requirement 2	*IfcSlab*.BASESLAB	Attribute	Name	-
	Loadbearing TRUE	Pset_ConcreteElementGeneral	ConstructionMethod	In Situ
			StrengthClass	C25/30
			ExposureClass	XC1
			StructuralClass	S4
			ReinforcementVolumeRatio	100
			ReinforcementStrengthClass	B450C
		Pset_SlabCommon	FireRating	
			IsExternal	-
			LoadBearing	TRUE
			Status	NEW
		Qto_SlabBaseQuantities	Depth	-
			Width	-
			Length	-
			Perimeter	-
			GrossVolume	-
			NetVolume	-

6.2 Verification of the uniqueness and completeness of data

As already widely discussed in the section of "RESEARCH AIM & METHODOLOGY" the article aims to identify a method of verification of the uniqueness and correctness of the association between cost item and geometric object.

Starting from structured cost data and a geometric model that meets the information requirements identified by IDS, a code has been developed for the association of IFC cost entities - *IfcCostItem* with IFC geometric entities - *IfcElement* (will not be discussed in this article), and after that another code has been developed for the verification and validation of the correctness and uniqueness of the process of association of cost items to geometric objects. This verification process is completely different from the current ones; in fact, currently the verifications are focused exclusively within the same domain. What the research does is verify the correctness and uniqueness of the information between two different domains (in the specific case geometric domain and cost domain).

The developed code was implemented using Python 3.10, IfcOpenShell, an open-source library (IfcOpenShell v0.7.0) and the IFC4_ADD2_TC1 - 4.0.2.1 (currently the official version).

Through the developed code it is possible to perform an analysis of the geometric model containing the price items. The analysis involves a detailed verification of the information contained in the geometric object of the model (PropertySet, Material, etc.) against the information contained in the price item (Sample Element, PropertySet, Material of Sample Element, etc.) stored in the cost database. In fact, the architecture of the cost item is not present inside of the analyzed geometric model, which contains instead the single entity of cost (*IfcCostItem*) useful for the definition of the estimate of the costs (cost schedule); this retrieves some key data from the unit cost item, such as name, description, or unit cost value (*IfcCostValue*). This will allow to maintain a constant relationship between the item from cost estimation and the unit cost item without weighing down the model of information stored in an external queryable database (Figure 5).

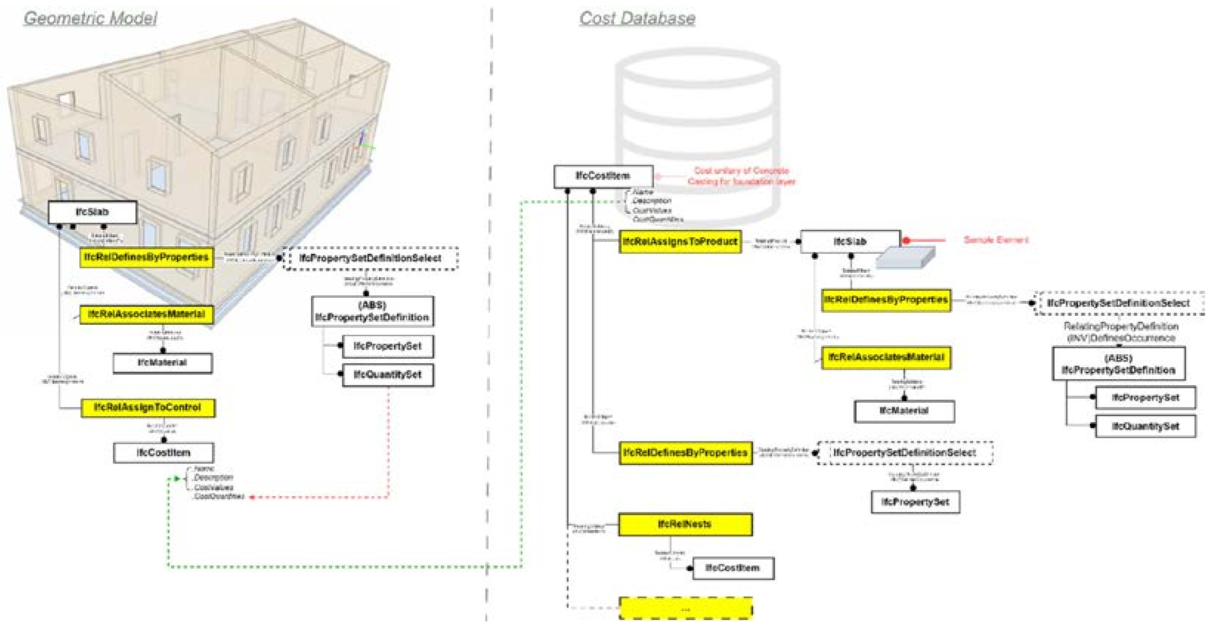


Fig. 5: Relation between geometric object data and cost item data

Due to the scope of the article the verification was performed on a limited number of geometric entities of the structural model: a sub foundation, a foundation, a slab and concrete masonry. Each of these entities is made of concrete cast in place and armed but having different characteristics (exposure class, strength class, structural class, etc.).

The data analysis begins by first identifying the geometric entities to which a cost had been associated. After that through a user interface based on manual input it comes chosen which relation object-cost to analyze. Starting from this choice, the code allows to extract the cost item associated with the geometric entity and, through a predetermined key (*IfcCostItem*.Name + *IfcCostItem*.Description), search the corresponding unit cost item within the cost database. Once the cost item is identified, the code proceeds by analyzing the properties and extracting the data to be verified; for example, the sample element associated with the cost item and the relative Pset_SlabCommon are analyzed to understand if it is a structural element (Loadbearing = True) or non-structural (Loadbearing = False), Figure 6.

```
#97=IfcCostItem('1$8jCZH8bFE97CyJuzD_2b',$,'Concrete casting for foundation layer', '...',.USERDEFINED.,(#96),(#95))
 - #45=IfcRelAssignsToProduct('3f5uwtK8r0ivS67zJKTVQU',$,'Rel cost-element','Rel between cost item and sample element',(#12),$,#14)
 - #14=IfcSlab('2942YU3sLCEvWbpvY3ug5Y',$,'Sample element of concrete foundation slab', '...',$,$,$,$,.BASESLAB.)
 - IfcSlab
 - BASESLAB
   ‣ #24=IfcRelDefinesByProperties('1qS4DR7EH8Yw0pP$KWTsjd',$,'Rel Pset','Rel between Pset-Sample Item',(#14),#23)
   ‣ #23=IfcPropertySet('3eHYyWf$j3o9iq4HBQt0uP',$,'Pset_SlabCommon',$,(#15,#16,#17,#18,#19,#20,#21,#22))
     ◦ #22=IfcPropertySingleValue('LoadBearing','Whether this component is carrying (YES) or not carrying (NO)',IfcBoolean(.T.),$)
```

Fig. 6: Query the cost item and the data it contains

The analysis continues by questioning the geometric entity and identifying the corresponding properties analyzed in the cost item; For example, we analyze the element class (*IfcSlab*), the PredefinedType attribute (BASESLAB) and its Pset_SlabCommon to check whether the element is structural (Loadbearing = True) or non-structural (Loadbearing = False), Figure 7.

```
#1881=IfcSlab('1r$167n5fDrxE0IVJzq9my',#19,'FND_PLA',$,'Platea:FND_PLA_30',#1868,#1880,'242873',.BASESLAB.)
 - IfcSlab
 - BASESLAB
   ‣ #1900=IfcRelDefinesByProperties('2zqfiK0TxYZV_kPQ7PQE8u',#19,$,$,(#1881),#1887)
   ‣ #1887=IfcPropertySet('2Unrwa5Dqbjdie587QU4TO',#19,'Pset_SlabCommon',$,(#242,#718,#719,#1883))
     ◦ #242=IfcPropertySingleValue('LoadBearing',$,IfcBoolean(.T.),$)
```

Fig. 7: Query the geometric object and the data it contains

After the IFC model query phase, the results are analysed and validated. A comparison of the data identifies any inconsistencies (Figure 8). These are reported to the user who can then decide which choice to take:

- keep the cost-object association unchanged while knowing that the cost item is not completely congruent with the geometric object. to identify a cost item;
- modify the cost item originally associated through the query of the cost database and choosing between the proposals identified or if they are not present to create a new cost item to be added to the database.

This last mode (creating a new entry to be added to the database) has not yet been implemented and will be part of the future developments of the research.

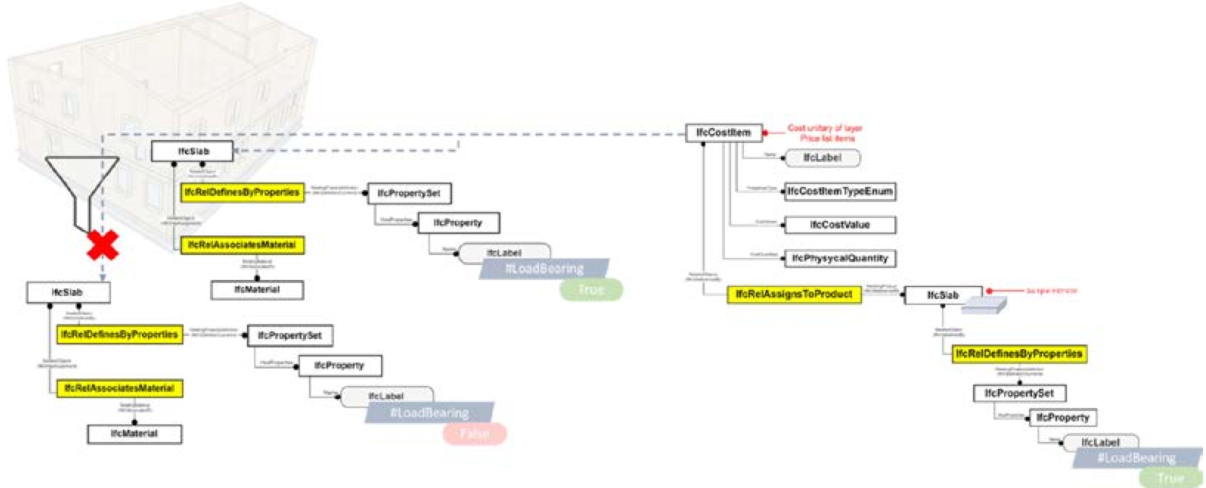
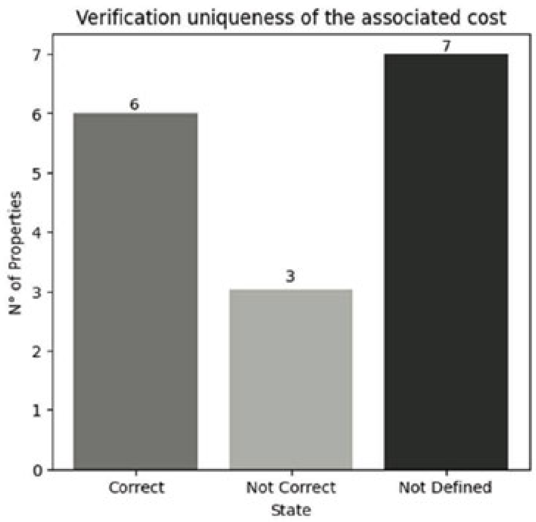


Fig. 8: Example of verification of the correctness of the association of the cost item to a geometric object

A report on the analysis of the output data is also saved in parallel with the display of the results; this report is for each individual association. In Figure 8 is shown an example of test verification performed on the association of the cost item of concrete casting for structural foundations and its geometric object (foundation) with relative data feedback. As we can see from the report obtained at the end of the test (Figure 9), the verification of the association of the cost item to the analyzed object provides the assessments on the current data. Therefore, it will be possible to understand the consistency or not of the data that the geometric object contains with the data contained in the associated cost item as visible in Table 2.



State	N° of Properties	Percentage
Correct	6	37.50%
Incorrect	3	18.75%
Not Defined	7	43.75%
Total	16	100.00%

Fig. 9: Report on the analysis of the output data

Table 2: Verified parameters between geometric object (*IfcSlab*) and associated cost item

Entity	Attribute/PSets	Parameter Name	Geometric Object	Cost Item	Check
IfcSlab	Attribute	PredefinedType	BASESLAB	BASESLAB	✓
	Pset_ConcreteElementGeneral	ConstructionMethod	In Situ	In Situ	✓
		StrengthClass	C20/25	C25/30	✗
		ExposureClass	XC1	XC1	✓
		StructuralClass	S1	S4	✗
		ReinforcementVolumeRatio	100	100	✓
		ReinforcementStrengthClass	-	B450C	ND
	Pset_SlabCommon	FireRating	-	-	ND
		IsExternal	FALSE	TRUE	✗
		LoadBearing	TRUE	TRUE	✓
		Status	-	NEW	ND
		AcousticRating	-	-	ND
		PitchAngle	-	-	ND
		ThermalTransmittance	-	-	ND
		Compartmentation	-	-	ND

7. DISCUSSION

This study is part of a larger research work that aims to digitize and standardize cost data and identify a new costs domain, that can ensure the verification of the correct association between cost items and geometric objects.

Considering the high uncertainty and inaccuracy of the information during the estimation processes is of fundamental importance:

- define the information requirements that the model must contain (Level Of Information Need) for a correct economic management;
- define an automated control procedure for the same information requirements (IDS) to avoid errors and time wasting;

- check the correctness and uniqueness of the cost items associated with geometric objects to ensure greater correctness of the cost estimate.

Nowadays cost estimation is one of the most critical tasks in the AEC/FM industry. Therefore, to support, verify and improve the quality of cost estimates, in public tendering, and reduce human error-prone, the study proposes the identification and applicability of a procedure for the verification of uniqueness of cost data assigned to geometric object within IFC data model. This scientific research has led technological attempts through the writing of a code in Python and through the support of the library IfcOpenShell. The results obtained are real, effective and scalable. The scalability of the hypothesized method has been demonstrated as it can also be implemented for other models. Currently, however, you can get these results only through code because current commercial applications do not allow user friendly implementations. The possibility of developing an executable to facilitate the verification of the model by an external user is being studied.

Currently, as seen in the literature, the approaches used do not provide for a verification of the correctness and uniqueness of the association between two different domains, cost and geometry. Typically, the verification is done within the geometric model considering only one domain (that of the model itself). In fact, usually only geometric interference and checks with the current regulations are carried out. While the goal of the research is to validate data between a plurality of domains (in this case the geometric domain and the cost domain) linked together and that can be contained in the same model. This causes numerous problems both in the phases of cost estimation and in the phases of construction of the work with consequent cost increases and possible disputes between customer/commissioning body and enterprise.

Nowadays, the only possible checks on the association of cost with a geometric object are made manually; there is no possibility for machines to understand information not structured and in natural language. For this reason, the goal of the research is to create a cost architecture to be associated with a geometric object, richer and more granular than a simple attribute associated in the model, allowing the verification of uniqueness and correctness of the data. The results of the research confirm the feasibility of the proposed method.

8. CONCLUSION

This research work is part of a larger project that will involve the relationship of the information of economic objects to the information of geometric objects. Specifically, the research shows how, in the AEC sector, it is essential to perform a verification of the associated information during the cost estimation phase for a correct management of cost data within construction projects. The research studies and experiments the application of a semi-automated method of verification of the cost data to ensure uniqueness and consistency of the information. This will allow to quickly and effectively verify if the cost information present in the project is consistent with what is stated within the geometric model.

Despite the many advantages that this application can provide, some limitations have been found in the proposed method including:

- standardisation of information and identification of requirements that the model must have (if the model does not follow the specified requirements, it is not possible to carry out cost verification); it is not possible to test the method on any IFC model received;
- need for detailed analysis of the information in the IFC data model for a clear understanding of the geometric object; it is not possible to identify the geometric objects from the class attributes alone (Name, description, TypeEnum, ecc.) but it is necessary to deepen the relationships that the same creates with other entities (*IfcMaterial*, *IfcPropertySet*, ecc.). A practical example is found among the objects lean concrete and slab foundation; they are both *IfcSlab*.BASESLAB and one of the ways to differentiate them is to analyze the LoadBearing single value (True or False) in the Pset_SlabCommon.

Although the method has been applied to a specific case study in the structural field, the methodology can be applied for several case studies. Future developments should include testing it in different areas and models for construction and large-scale application to verify its reliability. In addition, an application with user-friendly interface must be developed to ensure easier use of the tool.

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SEMANTIC WEB BASED INTEGRATION BETWEEN BIM COST AND GEOMETRIC DOMAINS

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ABSTRACT: *In the architecture, engineering, construction, and facilities management (AEC/FM) industry methodologies are needed to ensure the interoperability of data and effective management of information from different sources. Integration of the cost domain and cost estimation within the Building Information Model (BIM) in the AEC/FM sector is still an unresolved problem and one of the most critical tasks due to the lack of a standardised cost domain, especially in the tendering phase.*

To ensure interoperability between cost data and geometric data, this research aims to address this gap by analyzing methods of converting cost data into Linked Building Data, thereby defining a cost domain in the Semantic Web, by collecting them into a graph database. This allows for structuring a cost domain, translating an IFC based structure previously developed by the research group, visualizing it using a graph system, and connecting it to the BIM geometric domain. Furthermore, it is possible to extend the cost ontology previously identified in the IFC model and facilitate the queries and analysis of cost data currently fragmented and based on unstructured data.

The results show how Semantic Web technology can be used to improve data interoperability, develop a cost ontology, and join both cost data and BIM models.

KEYWORDS: *Semantic Web, Linked Building Data, IfcOWL, cost ontology, IFC, RDF, graph system.*

1. INTRODUCTION

The construction process is complex, dynamic and requires numerous interactions between the different actors involved. The sharing of different information, including information on the amount of physical components of the building, the planning plan, and the consumption of resources and costs is essential for accurate time and cost management.

Nowadays, in the Architecture, Engineering, and Construction (AEC) industry, the standard format used for information exchange is the Industry Foundation Classes (IFC), a neutral and open ISO standard by buildingSMART. Currently, the most recent IFC scheme is IFC4 ADD2 and contains about 1200 classes. BIM software developers can implement an exporter to convert respectively their native BIM format to the neutral IFC format.

Despite the clear advantages of data interoperability, which would otherwise only be feasible in proprietary BIM software, the IFC data model still has some limitations (Pauwels & Terkaj, 2016). These include, for example, the impossibility of extending it in a user-friendly way, the difficulty of developing applications with this template, due to the complexity of the schema expressed in EXPRESS format (Krijnen & Beetz, 2018), or the impossibility of relating data between the IFC file and other cloud historicized files. The IFC scheme is used as an interoperable format for sharing information, with the aim of being a supplier-independent exchange format, but not a fully integrated and comprehensive description of a project. This leads to an immense untapped potential of data in the AEC industry (Krijnen & Beetz, 2018). In comparison, the Semantic Web (SW) uses the Resource Description Framework (RDF) triple schema to store data and ontologies to enhance the semantic structure to make information machine-readable (Berners-Lee et al., 2001). It may also contain multiple ontologies, a formal and explicit specification of a shared conceptualisation (Gruber, 1993), covering specific areas not included in the IFC scheme (Rasmussen et al., 2017) and enabling the visualization and improvement of the interoperability of the IFC information model.

In order to overcome these limitations, this research is focused on the potential of SW. This research focuses on the conversion of the architecture of cost items, assumed and implemented in the IFC data model in a previous study carried out by the research group (Cassandro et al., 2023), to RDF using the emerging Linked Building Data

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Jacopo Cassandro, Claudio Mirarchi, Alberto Pavan, Andrea Zamborlini, Carlo Zanchetta, *Semantic Web Based Integration Between BIM Cost and Geometric Domains*, pp. 813-823, DOI 10.36253/979-12-215-0289-3.81

(LBD) modular ontologies as proposed by the W3C LBD CG (Bonduel et al., 2018). To validate what has been done in the previous study, the IFC-to-LBD converter presented by Bonduel et al. (2018) has been used. Information from IFC building models is extracted and transformed into Abox RDF graphs suited for usage in Linked Data applications.

The graph system will contain the relevant information of both the geometric model and the cost architecture with the related properties. Data translation within the SW will allow to query the model, associate the two different domains studied (geometric and cost) within a single environment, and view cost data and related architectures.

This paper develops following these steps. First, a detailed analysis of the literature to deepen the themes on the SW. Secondly, the identification of the conversion tools available to date for the transition from IFC to RDF and the subsequent validation and analysis of the results within a graph database. Finally, the conclusions and future works will be set out.

2. BACKGROUND

2.1 Literature review

The first research on the application of the SW in the AEC Industries dates back to the early 2000s; since then, their use has spread to more and more areas of the industry, producing interesting results in terms of number of publications and significance of results. Beetz et al. (2015) and Pauwels et al. (2017) analysed the reasons for the spread of SW in the AEC industry, identifying three main reasons: (1) Interoperability, (2) Liking across domains and (3) Logical inference and proofs.

The possibility of improving the Interoperability (1) relies on the SW structure which provides a way to store information in a computer-understandable manner, making possible the comprehension of the information involved in the process both by a human being and a machine.

The linking across domain (2) relies on the opportunity to create a unique web of linked data with information from all the different areas of the AEC process, (e.g. GIS, costs, energy, facility management, and so on).

The third motivation is the logical inference and proofs (3), which relies on the OWL language used for the semantic meaning. Correct use of the language offers the opportunity to infer more information from the original input, improving the web and allowing us to do more complex queries.

As we previously said, the usage of SW in the AEC involves different areas of the industry; a review of some of the most significant utilisations is reported below.

H. Abanda et al. (2011) proposed a SW based decision support system, which helps the government to speed up and automate the bureaucratic processes. This approach shows how SW could be a powerful ally for the PA to manage all the applications for a licence. In Karan et al. (2015) the SW is used to overcome heterogeneity problems, which came from the traditional methods of heterogeneous data sharing, generating IFC from semantic web query results. The IFC structure lends itself to a translation in linked data, which is why Zhao et al. (2020) suggested a method for IFC data merging based on miming the IFC structure with nodes and edges. The IFC graphs are merged and then restored in the starting files, implementing the information. Merging information through SW can be done not only using the same type of input, like different IFC files; in fact, Malinverni et al. (2022) used an approach that merges information from GIS and BIM models, producing an enriched model that has many benefits for the entire project life cycle. Also, the safety issues are affected using SW, and Zhang et al. (2015) developed a prototype of a new approach to organize, store, and re-use construction safety knowledge to produce a framework that supports automated job hazard analysis in BIM. Also, the safety issues are affected using SW, and Zhang et al. (2015) demonstrated a prototype of a new approach to organize, store, and re-use construction safety knowledge to produce a framework that supports automated job hazard analysis in BIM.

The damage and degradation analysis can also be positively affected by linked data and an interesting example is reported by Jung et al. (2021); they discussed an automatic approach to infer the causes of concrete cracks starting from information about pattern, location, and penetration status. The possibility to express human thinking and make a logical inference by machines thanks to ontologies can remove the issue of complex qualitative analysis during the process of identifying the cause of a crack.

The most meaningful domain analysed for this paper is 5D planning, for which can be found different approaches.

F. H. Abanda et al. (2011) developed an ontology-based technology in modelling information about labour costs that aims to facilitate decision-making among building developers in Cameroon; Vakaj et al. (2023) proposed a new domain ontology called Offsite Housing Ontology to support cost estimation about resources, products, and production processes. A further reference for cost estimation is Fürstenberg et al. (2021); they studied how semantic web technology can support BIM-based automated cost estimation and the related challenges, focused on Norwegian road projects.

The need to find ways of translating IFC into ontologies led to different approaches. The first interesting attempts can be found in Beetz et al. (2005), where two different approaches convert the EXPRESS schema of an IFC into an ontology in OWL notation: one using an intermediate step with an XSLT file between the XML file and the OWL, and a second which derives the OWL notation directly from the original EXPRESS schema format of the IFC. After that the approach evolved, leading to Beetz et al. (2009) which presented a semi-automatic way of lifting EXPRESS schemas into ontologies. Pauwels et al. (2015) analysed the correct ways to translate EXPRESS language into OWL. Hoang and Torma (2015) present the IFC2LD converter, a Java application with a Web interface, for converting IFC schemas into OWL2 ontologies and IFC data into RDF graphs aligned with the ontologies. Pauwels and Deursen (2015) present their online RDF to IFC conversion service, which converts an IFC into RDF triples. Continuing chronologically, Ismail et al. (2017) show a workflow for the automatic transformation of IFC into an object graph database; this method is based on a dynamic EXPRESS parser and a web script console that creates a meta graph inside Neo4j. Bonduel et al. (2018) developed a conversion of IFC to RDF using W3C Linked Building Data modular ontologies. The graphs are structured with three types of ontologies: BOT (building topology), PRODUCT (classification of building elements), and PROPS (building-related properties); the result is a more user-friendly graph than the ifcOWL Abox graphs.

2.2 Cost definition in IFC domains focus on IfcCostItem

Nowadays cost items are associated as attributes to geometric entities. However, to correctly return the analysis and economic evaluation processes, it is necessary to have cost architectures configured as more complex systems than a simple attribute associated with a geometric object. The IFC standard, through the cost class (*IfcCostItem*), offers the possibility of structuring a cost data model.

IfcCostItem is a non-geometric entity, a subclass of *IfcControl*, within IFC. *IfcCostItem* describes a cost or financial value with descriptive information that describes its context (BuildingSMART, 2022). It represents the cost of assets and services, the execution of works by a process, lifecycle cost, cost estimates, budgets, and more in the IFC standard.

IfcCostItem is characterized by its own attributes (PredefinedType, CostQuantites, and CostValue) and others inherited. An *IfcCostItem* has the possibility to instantiate one or more cost values (*IfcCostValue*). Other key features are that every single *IfcCostItem* can be nested to create cost assemblies through the *IfcRelNests* report, can be assigned to an *IfcProduct* through the *IfcRelAssignsToControl* report, may have an associated product through the *IfcRelAssignsToProduct* report or a resource through the *IfcRelAssignsToResource* report.

2.3 IfcOWL and Linked Building data (LBD)

In recent years, the area of cross-domain linking has received increasing attention. This area aims to combine data from various sources with construction data, management of information based on ontology, and analysis of the performance of buildings (Pauwels, Krijnen, et al., 2017). According to W3C, the Web Ontology Language (OWL) is a language designed to represent complex knowledge about objects, relationships between objects, and groups of objects in a way that can be exploited by computers (*IfcOWL - BuildingSMART Technical*, 2023.). BuildingSMART has developed the IfcOWL ontology based on these definitions, providing an OWL representation of the Industry Foundation Classes (IFC) schema, maintaining the same status as the Express schema. OWL concepts (OWL - Semantic Web Standards, 2023) can be used to construct RDF graphs, called OWL ontologies (Pauwels & Terkaj, 2016), enabling easy linking between the building data and material data, cost data, GIS data, and so forth. However, due to the complex structure of the IFC data model, the ifcOWL representation of geometric data is difficult to manage (Pauwels et al., 2017a).

Achieving interoperability between domains is the main purpose of the Linked Building Data (LBD) Community Group in the World Wide Web Consortium (W3C) (*The Linked Building Data Community Group*, 2021). LBD allows for storing construction data sources separately and processing them through digital and computer systems (Curry et al., 2013). This results in a set of data that can be utilized and interconnected. Expandability is a key aspect of AEC where most projects are fragmented, complex, and diverse. Using the LBD different ontologies can be mapped and enhanced each other, facilitating a more comprehensive and integrated approach to handling diverse data sources and formats within the AEC industry.

3. RESEARCH AIM & METHODOLOGY

The research aims to verify the effective possibility of associating the new cost domain with the geometric one through the SW. This will allow to relate different domains within the same environment to improve data sharing and interoperability. In addition, it will be possible to manage cost items no longer as simple attributes attached to a geometric object, but as real cost architectures, more complex, ensuring in the future also the ability to verify and validate the associated data.

The first study to examine the possibility of structuring a cost domain using Industry Foundation Classes (IFC) has already been addressed in Cassandro et al. (2023). In this work, based on the assumptions and limitations of previous research in Cassandro et al. (2023), has been translated the ontology previously developed in the Linked Building Data (LBD) format. This will allow us to relate the cost domain to the existing domains (in the specific case the geometric domain); in fact, SW technology is well-suited to link knowledge stored in different domains (Beetz et al., 2015; Pauwels, Zhang, et al., 2017).

The methodology adopted is characterized by the following steps presented in Figure 1:

1. Study of the State of the Art of the current practices and research connected to SW and graph database;
2. Analysis of IFC entities (*IfcCostItem* identified in the standard to manage the cost information) and how to translate it into LBD;
3. Translation of cost ontology, developed in Cassandro et al. (2023) from IFC to LBD through a tool developed by Bonduel et al. (2018);
4. Information validation in a graph database such as Neo4j;
5. Results of experimental research

A way to represent cost information by using SW was formulated, developed, and validated. This could provide the basis for the information exchange resources among information systems for the more user-friendly query of data and linking different domains. The next sections describe the mechanisms used to implement and test the method.

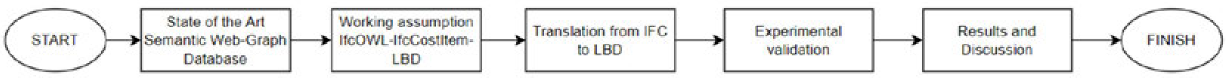

Fig. 1: Research Methodology

4. RESULTS

In this research, the case study is the same as that analysed by Cassandro et al. (2023). This allows to fully understand the differences between the methodologies adopted and to compare the results obtained during the two research. The case study is a wall composed of six layers; each layer corresponds to a different cost item within the regional price list (Lombardy Region) which must therefore be associated with the related geometric object, see Figure 2. These cost items have already been structured within the IFC data model.

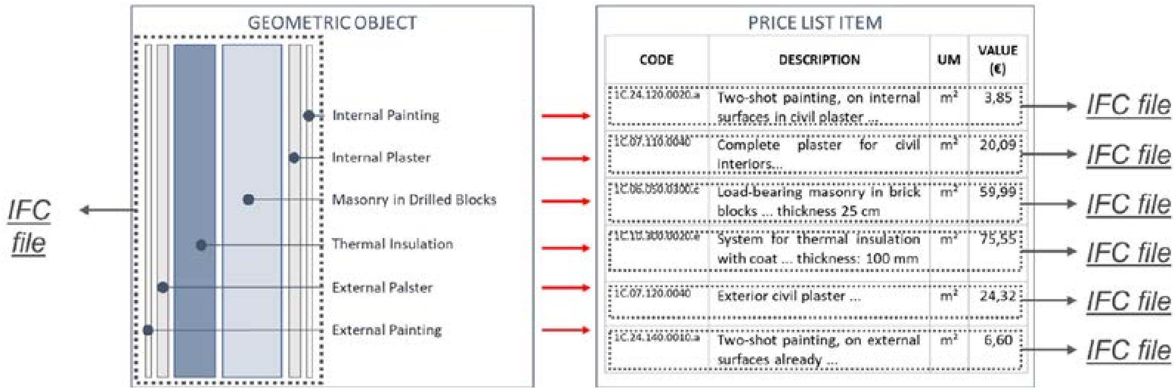

Fig. 2: Example layers of masonry and relative price items

Then the individual IFC files were converted into RDF format using the tool "IFCtoLBD[1]" developed by Jyrki Oraskari and Mathias Bonduel. This tool allows to convert an IFC file to a Turtle file described using BOT and optionally PRODUCT, PROPS, and GeoSPARQL (Bonduel et al., 2018).

The correct export specifications have been set thanks to Bonduel et al. (2018). For the correct output, it is necessary to activate the PROPS module of the ontology structure, which includes three levels of complexity. For the case study, Level 3 was selected (i.e., the most complete level). Thereby, the Blank node option was activated, which decreased the file size, exported RDF, and improved the readability. The output is a Terse RDF Triple Language (Turtle); a format made to express RDF data. This format uses triples made by subject, predicate, and object to represent information.

At this point the new file in Turtle format is loaded inside a graph database (in this specific case Neo4j is used); in this way, you can view the information and links between these (Figure 3). As visible from Figure 3 every entity is associated with a series of intrinsic attributes of the same one. IFC information is intrinsically interconnected and can naturally be represented by graphs. Figure 3 shows the IFC file for a painting cost item at the top and the corresponding data representation in a graph system at the bottom (nodes and edges). As it is visible, the graph representation is more intuitive in revealing the relationships between instances than the text based IFC.

Translating the IFC data model into a graphical system can lead to a simplified representation of the construction information and its relationships, as well as improving data query.

The developed methodology relies on an IFC, which contains both the geometrical information and cost information, inserted into the file using the appropriate classes previously studied in Cassandro et al. (2023). The creation and compilation of *IfcCostItem* classes has been implemented in Python using IfcOpenShell, as shown in Cassandro et al. (2023).

The conversion from IFC to an LBD was carried out using a tool developed by Bonduel et al. (2018). The correct exporter setting has been set after several attempts to get the type of LBD needed. Figure 4 shows all the cost item files, in RDF format, imported into the graph database and related to the geometric object (wall system). After that, the latter was also imported and displayed, visible in Figure 5.

The Neo4j graph database has been used to visualize the data. The Neosemantics plugin (n10s) was used to load RDF data and its associated vocabularies, including OWL, RDFS, SKOS, and others, into Neo4j. This plugin extends Neo4j's capabilities to work with semantic data in RDF format, allowing users to import, store, query, and analyze RDF data within the Neo4j graph database. It facilitates the integration of RDF-based knowledge graphs and linked data into Neo4j, enabling more comprehensive and semantic data modeling and analysis.

[1] https://github.com/jyrkioraskari/IFCtoLBD

```
ISO-10303-21;

HEADER;
...
FILE_SCHEMA(('IFC4'));
ENDSEC;

DATA;
#1=IFCSIUNIT(*,.AREAUNIT.,$,.SQUARE_METRE.);
#2=IFCSIUNIT(*,.LENGTHUNIT.,.MILLI.,.METRE.);
#3=IFCQUANTITYAREA('Surface','Internal painting surface',#1,1.,$);
#4=IFCCOSTVALUE('Cost of internal painting layer','Cost of internal painting layer. Cost from Lombardy regional price list item',IFCREAL(3.85),#1,'2023-01-01','2023-12-31','List Price',$,$,$);
#5=IFCCOSTITEM('27?l5oLxTFgOuuWWNG0qa0',$,'Internal painting layer','Pitturazione a due riprese, su superfici interne in intonaco civile ... a base di copolimeri vinilversatati, traspirante','OPERA COMPIUTA', '1C.24.12.00020.a', .USERDEFINED.,(#4),(#3));
#6=IFCCOVERING('0uDF3F9X1AH95xql13eHRh',$,'Sample element of the internal paint layer','Sample element of the internal paint layer. Thickness 10mm',$,$,$,$,.CLADDING.);
#7=IFCPROPERTYSINGLEVALUE('Combustible','Indication whether the object is made from combustible material (TRUE) or not (FALSE)',IFCBOOLEAN(.F.),$);
#8=IFCPROPERTYSINGLEVALUE('IsExternal','Indication whether the element is designed for use in the exterior (TRUE) or not (FALSE). If (TRUE) it is an external element and faces the outside of the building',IFCBOOLEAN(.F.),$);
#9=IFCPROPERTYSINGLEVALUE('Status','Status of the element, predominately used in renovation or retrofitting projects',IFCLABEL('NEW'),$);
#10=IFCPROPERTYSET('0J_IsCV6XF1akHYTFvNPBA',$,'Pset_CoveringCommon',$,(#7,#8,#9));
#11=IFCRELDEFINESBYPROPERTIES('0JJOEv14P0485AThmRuwOm',$,'Rel Pset','Rel between Pset-Sample item',(#6),#10);
#12=IFCQUANTITYLENGTH('Width','Nominal width (or thickness) of the internal painting layer',#2,10.,$);
#13=IFCQUANTITYAREA('GrossArea','Sum of all gross areas of the internal painting layer. No opening that is included in the covering is subtracted',#1,1.,$);
#14=IFCQUANTITYAREA('NetArea','Sum of all net areas of the internal painting layer. All openings that is included in the covering are subtracted',#1,1.,$);
#15=IFCELEMENTQUANTITY('1NYRgbSdjBZgnfp5QXan5',$,'Qto_CoveringBaseQuantities',$,'BaseQuantities',(#12,#13,#14));
#16=IFCRELDEFINESBYPROPERTIES('154jn9Y932SOUzipRQd7AE',$,'Rel Qto_CoveringBaseQuantities','Rel between Qto - Covering',(#6),#15);
#17=IFCMATERIAL('Emulsion resins','Material used in water paints based on resin emulsions','Interior Wall Paintings');
#18=IFCRELASSOCIATESMATERIAL('0BMjIgYTEJuBoldGp6xnv',$,'Rel to Material Covering','Rel between Material - Covering',(#6),#17);
#19=IFCRELASSIGNSTOPRODUCT('3ZJINrwl54w9gHX0FKLowq',$,'Rel internal painting layer','Rel between cost item and sample element of internal painting layer',(#5),$,#6);
ENDSEC;

END-ISO-10303-21;
```

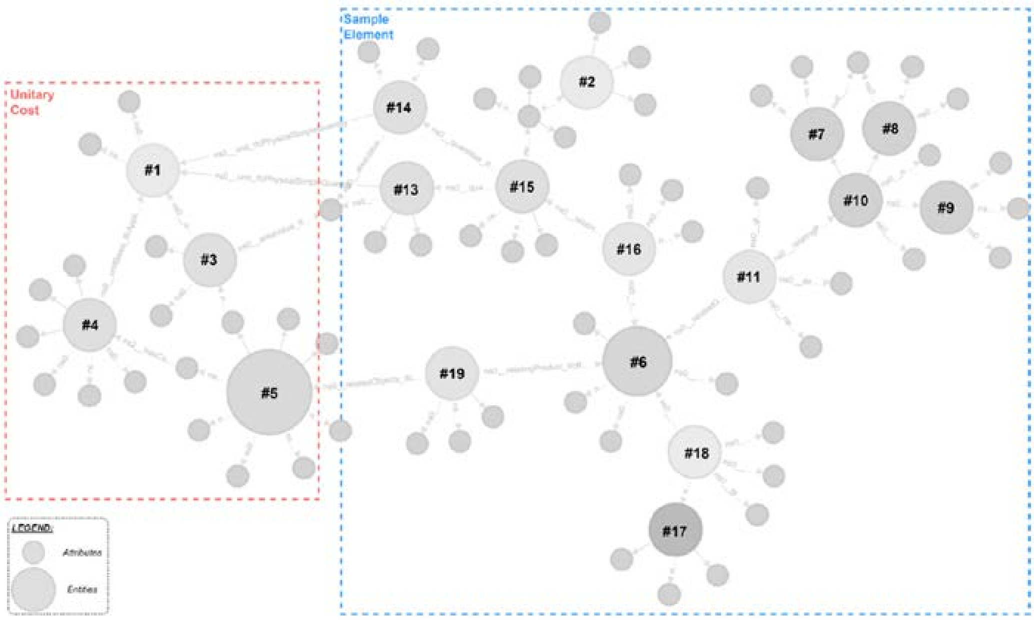

Fig. 3: Comparison between cost items in IFC format and RDF format

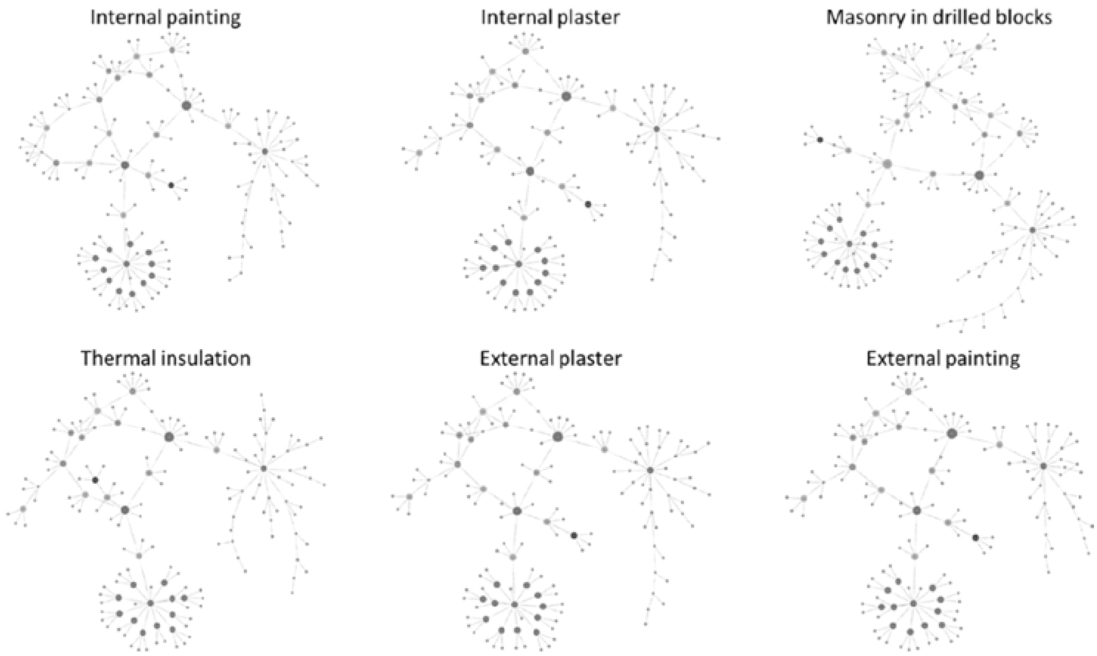

Fig. 4: Representation in the graph system of the six different cost items starting from IFC files

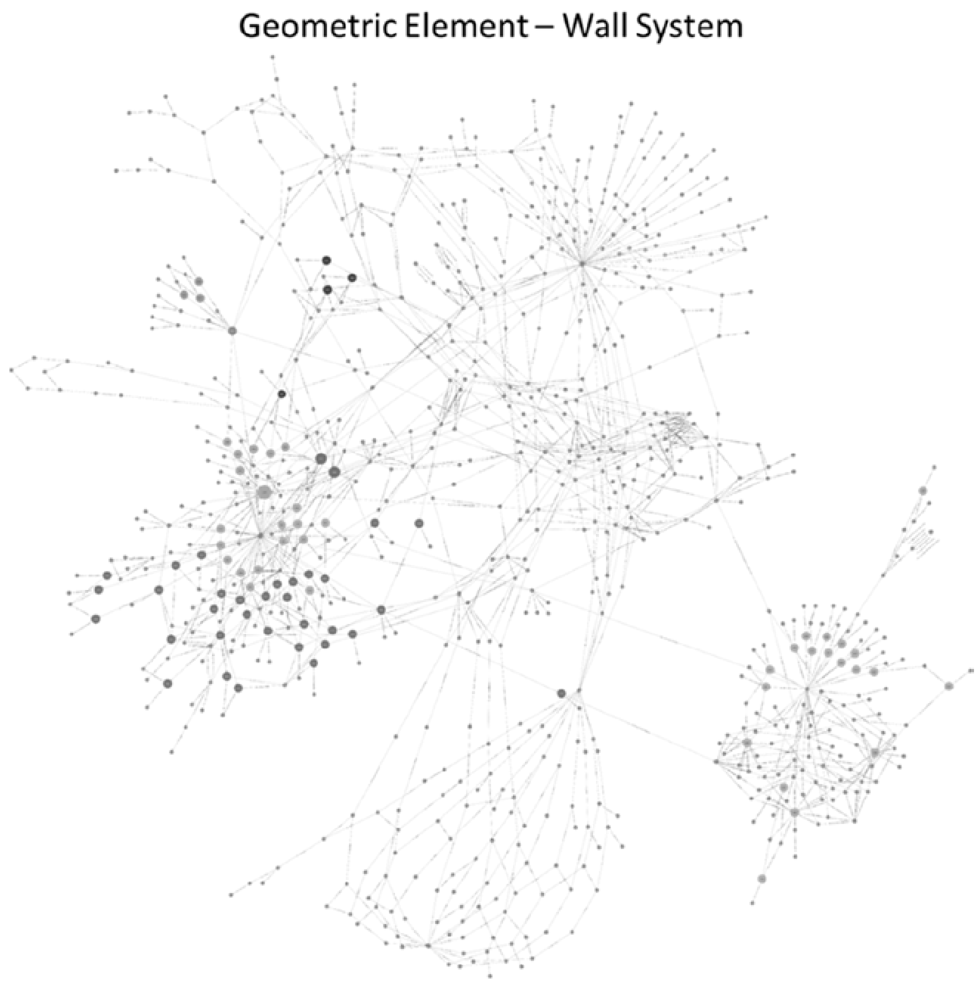

Fig. 5: Representation in the graph system of the geometric object (wall system) starting from IFC files

Through the Cypher script language, it was possible to work with the different Turtle format files available. Cypher is a declarative query language created specifically for working with graphs and interacting with the Neo4j database. Cypher queries are very expressive and readable and allow operations such as creating, editing, and querying data within the Neo4j database.

The first step was to load the data of the different files (Figure 6 - Script 1, Script 2). Subsequently, the data files were queried, and two node-entities were identified: *IfcCostItem (*Figure 6 – Script 3) which gathers all the architectural data related to individual cost items (within the cost domain) and *IfcElement* (Figure 7 - Script 7) which represents the geometric domain to which the cost item must be associated.

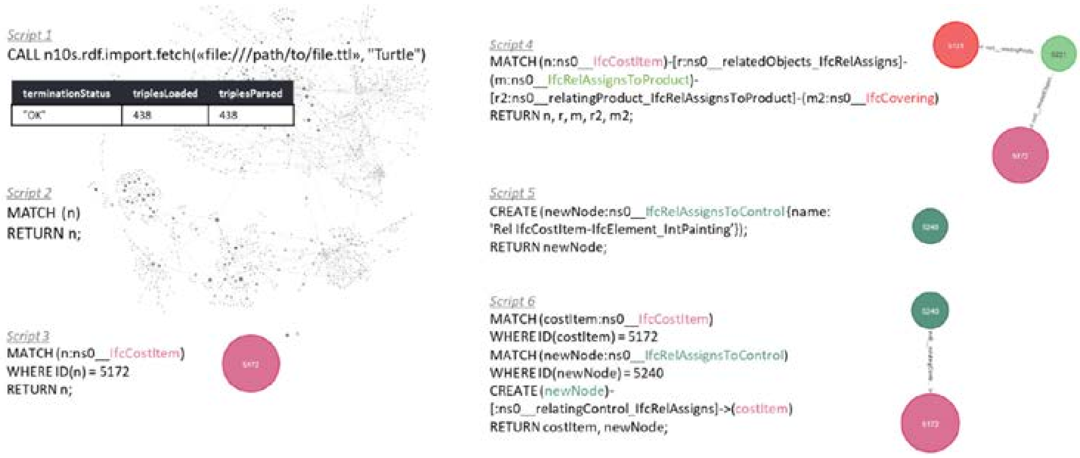

Fig. 6: First script sequence for *IfcCostItem-IfcCovering* connection (cost-layer painting)

Finally, the relationship between the two nodes-entities contained in the two domains has been created (Figure 7 – Script 9). As we can see in Figure 7, the two entities belonging to the two different domains (costs and geometry) have been connected using the logic intrinsic to the IFC data model. A node ("5240 - *IfcRelAssignsToControl*") has been created that corresponds to the exact IFC entity that ensures the connection between geometric entities and cost entities. This has led to the connection of the two different domains (cost and geometry).

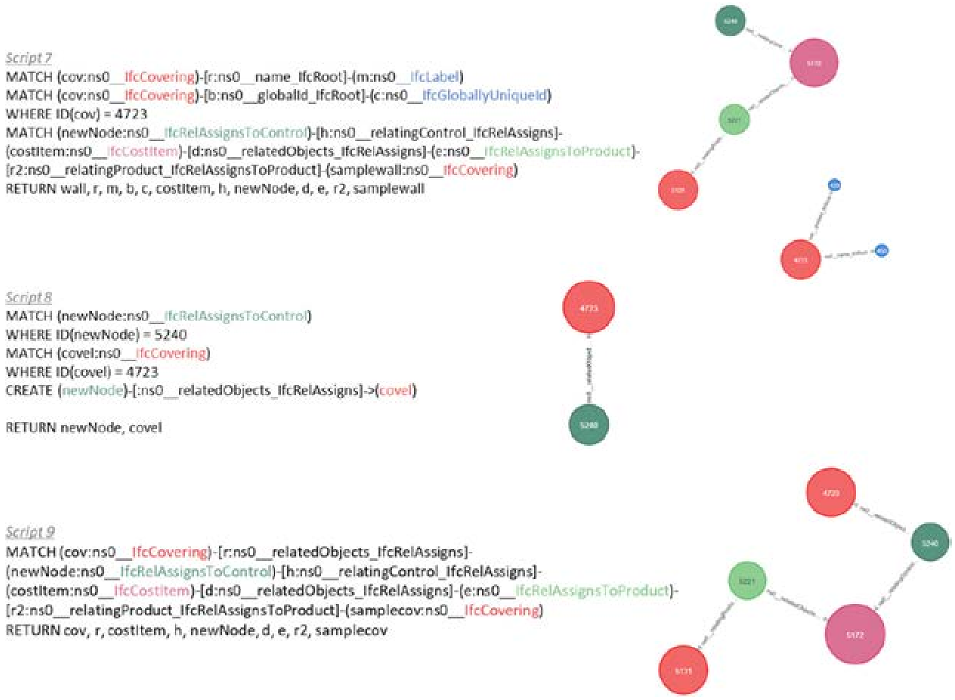

Fig. 7: Second script sequence for *IfcCostItem*-*IfcCovering* connection (cost-layer painting)

This procedure has been replicated for the remaining cost items to associate with the respective geometric objects to obtain a new system to graph containing the data of the geometric domain and the cost domain. Figure 8 shows the final output and a zoom on the association of the cost of the layer of internal painting (IfcCostItem_InternalPainting) to its geometric object (*IfcCovering*).

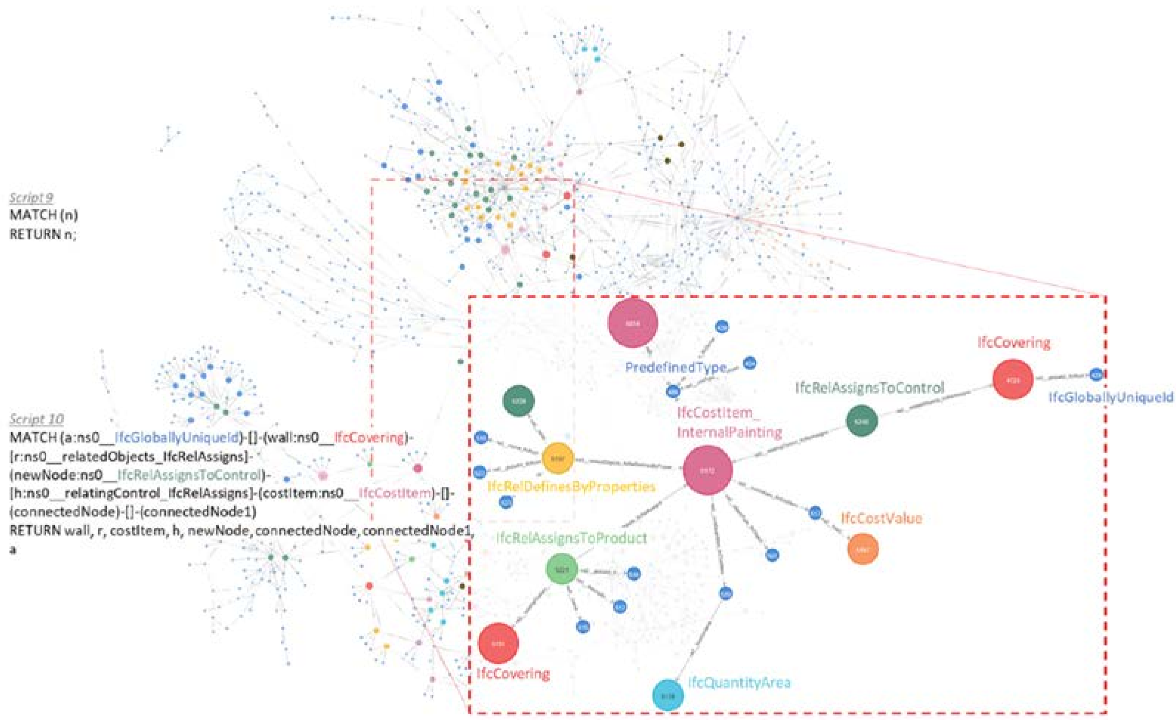

Fig. 8: Final output and zoom on the association of the cost to its geometric object (*IfcCovering*)

5. DISCUSSION

The study seeks to optimize and make the data of the cost items more user-friendly. Currently, these are displayed only as informational inputs, lines of code, or even simple attributes. The aim of the research is to focus on a subject of great interest and still cause numerous legal disputes. In the research, the possibilities and the limitations of the proposed method are highlighted based on the association of different domains within a graphic system. This would allow you to link different data from files even in different formats. This study presented how price elements can be instantiated as a graph and how their visualization allows us to better understand the logic of connection and relationship between entities. It has been studied the possibility of visualizing a new domain of cost for the price list of the Lombardy Region based on a graphical system to standardize and regulate the prices and the relative information.

Converting the IFC data model into a graph system can bring many advantages (Pauwels, Zhang, et al., 2017), (Zhu et al., 2022). The main reasons why converting IFC to a graph is an objective to be pursued are:

- a simplified representation of construction information (Silvescu & Caragea, 2019);
- clearer object relationships (Figure9);
- improved data integration and interoperability (Rodriguez & Neubauer, 2010), (Mazairac & Beetz, 2013);
- improved query and processing information (Pérez et al., 2010).

However, even if this methodology makes the data more visually intuitive, due to the limitations of the current tools available, it is not yet possible to convert the information in the IFC data model into RDF in a simplified way. A further limitation is due to the use of a programming language to query, create, and associate data belonging to different domains. This causes problems in a sector, the AEC, which is only beginning in recent years to interface with these new technologies.

This research has led to technological attempts made through the writing first in IfcOpenShell of individual cost items and then in RDF format for their association to the geometric domain and their simplified visualization; in this way, it is not necessary to understand the logic behind the IFC data model. The achievement of results that are real, effective, and scalable confirms the scalability of the method as it can also be implemented for other list items.

6. CONCLUSION

The results show how SW technology can be used to show and relate the cost domain for construction projects to different domains, such as the geometric domain. Starting from the IFC data model, the cost domain has been translated into LBD ontology thanks to the IFCtoLBD converter developed by Bonduel et al. (2018). In fact, due to the complex structure of the IFC data model, the LBD representation makes it easier for stakeholders to visualize and manage the data contained in the models. The IFCtoLBD converter developed by JURI uses the smallest BOT, PRODUCT, and PROPS ontologies to better separate and represent data (Bonduel et al., 2018).

In this study, the proposed architecture for the new cost domain, developed and validated by Cassandro et al. (2023), can be easily visualized within the graphical database. As a result, individual cost items and related information become readily accessible in the graphical database. Moreover, these elements can be queried individually, associated with their corresponding geometric objects, or even extended by creating new nodes and relationships.

During the study, several limitations were identified. Firstly, the complexity of data in the AEC industry can be more difficult due to the variety of information involved, demanding a deep understanding to integrate data into LBD format. Secondly, the AEC domain includes numerous standards and ontologies, which makes it difficult to ensure compliance with all relevant standards (e.g., IFC) when integrating data into LBD. Finally, interoperability remains a concern as not all software platforms are equipped to handle LBD, posing difficulties in achieving seamless data integration and interoperability across different platforms.

For future work, it is essential to prototype and extend the concepts explored in this study. In addition, the development of an extension for the converter to improve data translation should be considered.

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ONTOLOGY-BASED CONSTRUCTION INSPECTION PLANNING: A CASE STUDY OF THERMAL BUILDING INSULATION

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ABSTRACT**:** *Poor construction quality is one of the most significant challenges for the construction industry. However, failures can be avoided or minimized by inspections based on detailed quality inspection plans as a part of quality assurance. Therefore, structured and project-specific planning of inspection plans is required to provide inspectors with the right information.*

Nevertheless, inspection planning is mainly manual, dependent on the individual's experience and high level of effort. As a result, inspection planning is often neglected and limited to providing general checklists that often lack semantically rich descriptions and are unspecific concerning individual project requirements. Furthermore, proper planning of inspections requires multiple information sources, such as building design, schedules, contractual and supplier guidelines, and standards, all of which must be provided or linked via an information model. Current research lacks an adequate formalized knowledge model to provide the knowledge-driven inspection planning process with the necessary domain knowledge to support inspection planning with heterogeneous information defined in isolated systems.

Therefore, this paper extends the Ontology for Construction Quality Assurance (OCQA) with the OCQA-Thermal Insulation (OCQA-TI) to formalize thermal insulation inspection planning knowledge. The OCQA offers a new linked data model that provides explicit knowledge of quality inspection planning. The development of the OCQA-TI follows the Linked Open Terms (LOT) methodology and is implemented using the Web Ontology Language (OWL).

The proposed ontology is evaluated using various approaches, including automatic consistency checking, answering competency questions, and criteria-based evaluation. The results indicate that the OCQA-TI can provide inspectors with relevant inspection planning knowledge and integrate various related information streams, thus providing a more comprehensive and efficient approach to insulation inspection planning. The functionality of OCQA-TI enables the fulfillment of increased sustainability and energy efficiency requirements by providing insulation inspection knowledge.

KEYWORDS: *semantic web, building insulation, ontology, quality assurance in construction, inspection planning*

1. INTRODUCTION

Construction faces a significant quality problem, evidenced by an analysis by the German insurance company VHV showing that the total cost of reported damage claims has risen for years (Böhmer et al., 2022). A study by BauInfoConsult (2022) concurred, assuming a defective cost share of 12.8% of the industry turnover. With a total construction industry turnover of 143 billion euros in 2020 issued by the German Construction Industry Federation, the study extrapolates error costs of approximately 18.3 billion euros (BauInfoConsult, 2022).

Research and practice approaches have primarily focused on defect management yet have often neglected proactive defect prevention through inspection planning (Seiß, 2022). However, proactive inspection planning could avoid many errors and save costs. The VHV Report shows that approximately 58% of the causes of damage can be traced to avoidable execution and assembly errors as well as interface and communication problems. In addition, inadequate construction supervision accounts for approximately 7% of the causes of damage (Böhmer et al., 2022). Thus, a proactive, construction-accompanying quality assurance approach can address approximately 65% of all causes of damage.

Currently, energy efficiency and building sustainability requirements are increasing significantly worldwide. The

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Sebastian Seiß, Markus Boden, Jürgen Melzner, Yuan Zheng, Delval Thibaut, Rayan El Chamaa, *Ontology-Based Construction Inspection Planning: A Case Study of Thermal Building Insulation,* pp. 824-836, DOI 10.36253/979-12-215-0289-3.82

European Union has set targets for the construction and real estate industry's energy future. Climate neutrality in the building sector is to be achieved by 2050. Hence, new buildings must be constructed to the zero-emissions standard as early as 2028 (European Parliament, 2023). In the specific domain of insulation, quality assurance is particularly important. Insulation is crucial to buildings' energy efficiency, thermal resistance, and interior comfort since poor insulation installation and use can lead to heat loss, thermal bridges, moisture problems, and an overall decline in a building's energy performance (Sassine, 2013).

National policies were implemented after the oil shocks of the 1970s and the subsequent energy crisis to meet the requirements of stricter insulation and energy efficiency regulations. These policies led to adopting standards in France, such as the "*Documents Techniques Unifiés*" and the RT 2012 and RE2020 rules, regulating the materials used and their installation methods while quantifying buildings' losses, gains, and energy needs. However, the practical application of these rules has sometimes been questionable due to negligence or ignorance. Hence, it is difficult for a conventional inspection to identify potential defects since the insulation materials are always covered with various finishing elements (Antoine Szeflinski, 2007).

Non-destructive testing plays a crucial role in addressing these issues, allowing for precise recognition of construction phases, authentic elements, original and restoration materials, construction techniques, deterioration, durability, and structural strength. These are essential for assessing the energy and environmental performance of the building envelope. Visual tests, thermographic tests, sonic and ultrasonic tests, thermal flux measurements, and microclimate analyses are used in energy audits to obtain accurate results (LUCCHI, 2011). Notably, thermal insulation implementation inspections often focus on performance after completing the construction work. Nonetheless, this approach has a major drawback: a delay in detecting implementation defects. While waiting for performance inspections, quality problems can develop and become more difficult and costly to correct.

Therefore, considering corresponding inspection plans to guarantee the quality of finishing trades such as thermal insulation and meet the expanding quality requirements is necessary. However, quality assurance in the building industry concentrates on shell construction trades (Berner et al., 2015), while finishing trades often cause increased costs due to defects. In analyzing the BSB's quality inspections during construction, damage to thermal insulation accounts for a comparatively high 10.7% of total damage (Böhmer et al., 2020). France's heat and climate protection ordinance has led to a steady increase in the proportion of thermal insulation measures (Böhmer et al., 2020). Sales of External Thermal Insulation Composite Systems (ETICSs) have also steadily risen in Germany since 2018 (Statista, 2023). In parallel, the number of defects caused by ETICS has also increased. For example, building projects with ETICS are often affected by defects such as cracking, moisture penetration, and delamination (Böhmer et al., 2020).

Hence, introducing inspections of thermal insulation implementation throughout the construction process would be beneficial in addressing this problem (Zhong, 2012). This approach would allow for early defect detection and correction, implementation quality improvement, and optimal energy performance assurance in buildings from completion. Thus, exploring automation solutions to evaluate inspections would be imperative to bridge the gap between regulatory standards and on-site inspections. However, to our knowledge, there is still a lack of a structured and computable representation for formalizing the thermal installation regulatory standards. Meanwhile, the interoperability between standards and the on-site inspection information also remains. Ontology is known as a formal specification of the domain knowledge, which has been widely explored in the construction domain to facilitate knowledge management and information integration issues (Pauwels et al. 2017). But an ontology that is adequate to represent specific domain knowledge of the thermal installation quality inspection is still missing. Therefore, in this research, we aim to extend the Ontology for Construction Quality Assurance (OCQA) for involving the specific domain knowledge for the thermal installation inspection process. The proposed ontology aims to formalize thermal insulation inspection planning knowledge and link the on-site inspection information to achieve an automated evaluation of the thermal insulation evaluation. Inspections related to thermal insulation require the integration of data from various and heterogeneous sources, and the choice of technologies associated with ontologies was made to provide a framework for aligning and connecting disparate knowledge.

This paper is structured as follows. Sections 1 and 2 provide a general review of quality assurance and thermal insulation. Section 3 reviews the work on ontologies related to general inspection planning, while Section 4 describes the methodology used to develop the proposed ontology. Next, Section 5 discusses the specifications of OCQA-Thermal Insulation (OCQA-TI) ontology, while Section 6 provides a methodological conceptualization and implementation, which is evaluated using an example in Section 7. Finally, Section 8 discusses the limitations and contributions of the research and provides conclusions.

2. BACKGROUND

2.1 Quality Assurance and Inspection in Construction

Presently, there is a greater focus on comprehensive quality inspections and defect management to satisfy contractors in their construction projects until the client's final acceptance. However, despite these efforts, many gaps and discrepancies are still identified near the project's end. The issues are related to a lack of on-site personnel for managing quality and defects, an overwhelming workload to meet deadlines, non-unified checklists with much manual paperwork, poor communication among different project stakeholders, and a complex and labor-intensive interior finishing process. These problems require additional work to rectify the defects, often leading to project delays (Young S. Kim, 2008). When defects are detected after acceptance, the contractor has claims, so for executing companies, the expense of eliminating defects is worth avoiding defective work at all costs. Moreover, the services of the subcontractors must be checked for defects. Indeed, when a subcontractor's defect is unrecognized before the execution and leads to a defective overall performance, it results in a renewed execution (Langen & Schiffers, 2005).

Currently, construction projects have become increasingly complex. Hence, the more complex the construction projects and processes, the greater the quality risks and the relevance of undistributed information and communication processes in the planning and construction process (Böhmer et al., 2022), often leading to avoidable errors. In addition, decisions regarding quality inspections, including construction activities not to overlook and tasks to inspect, the quality data to be collected and verified, and the acceptance criteria for quality, are evaluated on-site by inspectors based on their previous experiences, which can vary from one inspector to another (Tan, 2010). This variation may arise for several reasons, such as a lack or absence of knowledge concerning regulations or feeling overwhelmed by the amount of regulatory text referenced for applicable provisions during quality inspections. As a result, manual verification of construction quality compliance has been a time-consuming and error-prone task (C. Eastman, 2009).

Therefore, construction inspectors require assistance with planning inspections to effectively define inspection objectives, explore various options, and efficiently allocate inspection resources. Thus, the inspection planning process can be divided into four steps (Lin, 2018) used to specify inspections by answering key inspection planning questions (DIN9001, VDI2619). First, the necessity of inspecting a characteristic (what?) is determined, and the associated inspection objects are defined. Second, the inspection time (when?), frequency (how many?), and scope (how much?) are determined. The third step defines the inspection procedure (how should the inspection be conducted?) and equipment (what materials are required for the inspection?), which must be simultaneously conducted since they are interdependent. This step also includes the inspection location (where is the inspection?) and the inspector (who is inspecting?). Finally, the fourth step determines the recording, management, and evaluation of the collected inspection data (Lin, 2018).

Furthermore, the agreed quality must be clarified as a building requirement to assess the objective quality and secure the success of construction work. In Germany, this clarification results from the general contractual conditions, the performance specifications, and the technical contractual conditions, according to §1 Para. 2 VOB/B. The construction target and, thus, the quality requirements of each construction project vary according to the project-specific performance specifications and contract components. A minimum set of requirements is ensured in German construction law in §1 para. 1 VOB/B by the obligatory agreement on the provisions of VOB/C, the General Technical Terms of Contract for Construction Work (*VOB*, 2016).

Moreover, verification in the form of testing activities is necessary per DIN EN ISO 9000 to ensure the quality of construction projects. Therefore, meeting the specified requirements should be verified using objective proof (ISO 9000:2015). In the construction industry, these inspection activities are conducted with structural acceptances divided into the following types: internal acceptance (according to the quality management plan) and acceptance under public law. Hence, a defect exists if the executed construction work deviates negatively from the contractual construction target (Berner et al., 2015).

2.2 Semantic Web and Ontologies

Data in the construction industry is generated in isolated systems and exchanged using various file formats, often with an insufficiently described relationship. The semantic web and associated linked data concept offers technical standards for a comprehensive, machine-readable exchange of heterogeneous information (Beetz et al., 2021). In a semantic web context, ontologies describe a shared conceptualization of a specified knowledge domain in a community of users. Therefore, using semantic web technologies, an ontology represents a part of the real world in a semantic model (Synak et al. 2009).

The foundational semantic web language is the Resource Description Framework (RDF), and its data structure is organized in triplicate, consisting of a subject, predicate, and object. The subjects and objects are depicted as nodes, while predicates are represented as edges connecting these nodes. As such, these RDF structures are often referred to as triplestores or RDF stores (Hitzler et al., 2008). These RDF structures are characterized by directed and labeled graphs (Herman 2004).

The capabilities of the RDF are further enhanced by additional languages and schemas, such as the Resource Description Framework Schema (RDF-S) and the Ontology Web Language (OWL). For instance, RDF-S broadens the scope of the RDF schema by introducing classes and defining properties. In comparison, the OWL utilizes RDF-F to represent ontologies and extends the model by establishing constraints among classes, properties, and entities (Allemang et al., 2020).

Typically, ontology knowledge provided by semantic web technologies is divided into two main components: an assertion box (A-box) and a terminology box (T-box). In some semantic web applications leveraging a specific rule language, an additional component, a rule box (R-box), is included. The T-box holds intentional knowledge or the terminology outlining a specific domain using a database schema-like vocabulary that incorporates classes, properties, and relations. The T-box's concepts remain constant and do not vary over time. In contrast, the A-box manages the facts tied to the terminology terms introduced by the T-box. In this way, the A-box instantiates the predefined classes and conceptual model with real-world individuals. It encompasses extensional knowledge about specific situations likely to change over time (Baader et al. 2007; Baader et al. 2017; Pauwels et al. 2017).

3. ONTOLOGY WORKS RELATED TO INSPECTION PLANNING

As we step into a new era of digital transformation in various sectors, there has been a surge of research and development efforts in the field of ontologies. Some have been particularly related to construction and inspection planning. Thus, this section aims to provide a comprehensive literature review starting with general ontology work in the construction domain and ontologies used in inspection planning.

Recently, ontologies have become increasingly relevant in the AEC sector, addressing challenges like data integration and knowledge management (Pauwels et al. 2017). Various ontologies have been created in the construction field, including the generic e-COGNOS (El-Diraby et al. 2011) and IC-PRO-Onto (El-Gohary et al. 2010). These ontologies, while comprehensive, lack a detailed representation of construction inspection, necessitating further expansion for accurate inspection representation. Therefore, further development resulted in Digital Construction Ontologies (DiCon) by Zheng et al. (2021), defining broader construction workflow-related entities and successfully integrating data from diverse systems. Beyond construction, ontologies such as IFCOWL (Pauwels 2016) and the Building Topology Ontology (BOT) by Rasmussen et al. (2020) have offered valuable semantic structures for building information modeling and topological concepts, respectively.

In the realm of construction execution, ontologies have made significant strides in addressing issues such as construction data integration and knowledge management. Therefore, this section focuses on ontologies specifically tailored to construction quality inspection. Zhong et al. (2012a, 2012b) introduced the CQIEOntology for quality management. This ontology primarily focuses on quality compliance checking while supporting inspection planning in an ancillary manner. The ontology expresses complex constraints usually found in quality regulations using the Semantic Web Rule Language (SWRL). This ontology-based approach enhances the construction quality inspection process by integrating these regulations within the construction process.

Martinez (2019) proposed an alternative method involving SPARQL queries to retrieve quality regulations based on the construction object and materials used, as specified in the ontology. Although the study primarily focused on predefined checklists, it overlooked the planning and preparation of quality inspections. The research aimed to primarily explore offsite manufacturing processes related to drywall steel frames.

Lastly, Xu (2019, 2021) developed the Highway Construction Inspection Ontology (HCIOntology), formulating inspections based on pay items and specifications defined by the Indiana Department of Transportation. The user interface allows users to select predefined check items based on to-be-inspected pay items, supported by a risk matrix. These check items contain various fixed characteristics of inspections, such as frequencies, objectives, checking conditions, and training documents.

The review demonstrated that ontologies are viable for formalizing construction domain knowledge. However, it also indicated insufficient effort is spent integrating diverse information sources and making inspection planning knowledge of multiple domains (e.g., trades) available. Additionally, the inspections are inadequately described and undefined in light of the shared terminologies provided by ISO 9000, ISO 9001, and DIN 55350. Research has also neglected inspection planning for finishing trades, specifically the thermal insulation trade. Therefore, this research paper aims to 1) prove the reliability of OCQA for multiple trades, 2) provide knowledge for inspection planning of the thermal insulation trade, and 3) integrate heterogeneous information defined in isolated systems related to thermal insulation inspection planning.

4. METHODOLOGY

Concerning OCQA, a hybrid approach was adopted based on the Linked Open Terms (LOT) methodology developed by Poveda et al. (2022). LOT was designed as an industry-oriented ontology development methodology more related to practical engineering cases than others and has been well evaluated through practical use. Furthermore, the activities in applying LOT are described in detail and documented on GitHub (Poveda-Villalón et al., 2022). The detailed process of the ontology's development methodology is illustrated in Figure 1. The process is divided into four phases: 1) specification, 2) implementation, 3) publication, and 4) maintenance.

The specification phase defines the ontology's scope, purpose, use cases, users, and requirements (Fernández-López, M. et al., 1997). Throughout the entire ontology engineering process, knowledge acquisition remains an ongoing and iterative process. Thus, a conceptualization is created, incorporating existing ontologies and encoding by building upon the specification. Subsequently, the developed ontology is evaluated to ensure its effectiveness.

Various evaluation methods are employed to assess the developed ontology. Following the evaluation phase, the ontology is documented using a Hypertext Markup Language (HTML) sheet. For wider accessibility, the ontology is published on GitHub, enabling a broad range of users and developers to access and reuse it.

GitHub is a valuable platform for ontology maintenance, facilitating collaboration and version control based on a repository (GitHub, 2020). It ensures the ontology remains up-to-date and well-maintained for its users and stakeholders. Thus, the following sections present the process steps of specification, implementation, and publication.

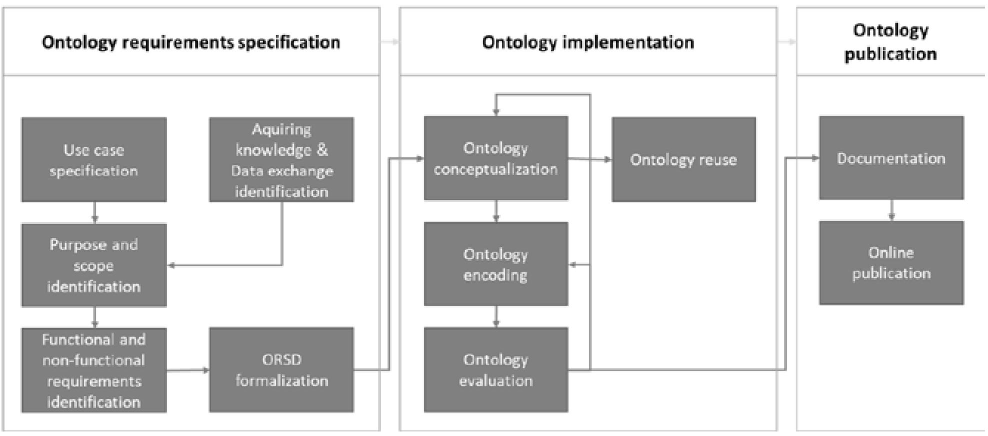

Fig. 1: Ontology development methodology according to Poveda-Villalón et al. (2022)

5. SPECIFICATION

This specification aims to create a formal document in natural language, utilizing competency questions (CQs) as the fundamental requirements (Fernández-López, M. et al., 1997). These CQs are derived from predefined use cases, aligning with the purpose and scope of the respective ontology. The resulting specification document is available on GitHub (Poveda-Villalón et al., 2022). The subsequent discussion formalizes the specification process steps.

Purpose: The ontology aims to formalize inspection plans for the domain of thermal insulation and related information of required domains, providing a shared representation of insulation inspection planning knowledge that specifies the terminology, semantics, and relations of inspection planning in the domain of thermal insulation. The terminology is defined according to DIN 55350:2021 and ISO 9000. Therefore, the purposes of the ontology can be summarized as follows:

1) providing a vocabulary for describing inspection plans and inspections for thermal insulation,
2) supporting manual inspection planning by providing detailed inspection planning knowledge,
3) supporting quality assurance decisions, and
4) strengthening the quality awareness of the staff.

Scope: OCQA-TI mainly focuses on representing the implementation of thermal insulation to ensure its proper installation and performance in new buildings and renovation. It provides structured knowledge on the optimal ways to install thermal insulation depending on the product and technique used while describing the necessary inspections, tests, equipment, and norms required to ensure its quality. Critically, our research focuses exclusively on process planning and the quality assurance of thermal insulation installation.

Use cases: The intended use cases of the ontology can be summarized as follows:

1) information retrieval by using queries,
2) heterogeneous data integration from isolated software solutions,
3) inspection planning support by querying inspection planning knowledge, and
4) inspection plan validation by reasoning.

End users: End users are project managers and management teams responsible for construction supervision, including inspectors, object planners, and building owners, depending on the project organization. In addition, the contractors can use the test plans provided for internal quality assurance. Notably, the users described do not use the ontology directly but interact with it via a software application. The ontology represents a substructure (backend) of software and is only used directly by developers (backend/substructure). Developers program software applications based on the ontology and store the data from heterogeneous sources in the ontology. End users use the ontology via an interface (superstructure or frontend) that ensures user-friendly operation (frontend/superstructure). For this purpose, users are provided with predefined queries for information or inspection planning knowledge retrieval.

Non-functional requirements (NFRs): NFRs pertain to how a system should perform, behave, and operate rather than focusing on what it should accomplish. In the field of construction ontologies, various studies have outlined NFRs, which can be summarized as follows: 1) coverage/sufficiency, 2) consistency, 3) usability, 4) extendibility/reusability, and 5) clarity and conciseness (Costin, A. and Eastman, C., 2017; Zhou et al., 2016; El-Gohary and El-Diraby, 2010; Zheng et al., 2021). These defined NFRs serve as evaluation criteria addressed through various evaluation methods.

Functional requirements (FRs): FRs are CQs aligned with the predefined use case of information retrieval. Table 1 provides a comprehensive list of the CQs that the proposed ontology aims to address based on questions for inspection planning from mechanical engineering that have been extended (Linß, 2018; Marxer et al., 2021).

Table 1: CQs related to the use case information retrieval.

Information retrieval
1. What are the characteristics being inspected?
2. What are the related entities of an inspection?
a. Where is the inspection location?
b. Who is responsible for the inspection?
c. What is the norm related to the inspection?
d. What equipment is required for the inspection?
3. What are the precedent and subsequent inspections?
4. What procedures are required for the inspection?
5. When is the start and end date of the inspection?

6. ONTOLOGY CONCEPTUALIZATION AND IMPLEMENTATION

6.1 Introducing the Ontology for Construction Quality Assurance (OCQA)

The basis for this work is the OCQA ontology (Seiß, 2022), designed to provide information about quality inspections in construction to support inspection planning. The main entities of the OCQA are the inspection, inspection plan, and regulations. The OCQA has a modular structure and can be supplemented as desired with inspection knowledge from different trades. Therefore, the OCQA-TI is designed as a trade-specific extension of the OCQA ontology. In addition, the Digital Construction Ontology (DiCon), with its previously described concepts for construction workflow, including agents, processes, and equipment, is integrated into the OCQA, extending the DiCon with detailed knowledge about inspection plans (Seiß, 2022).

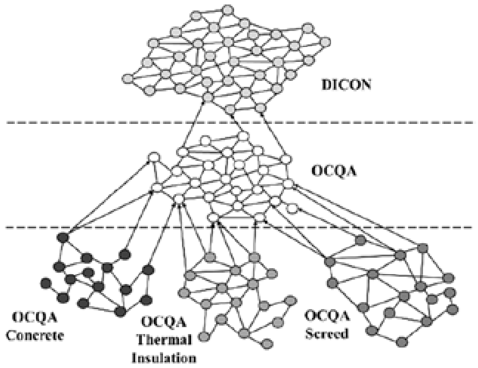

Fig.2: OCQA-TI as an extension of the OCQA

The integration among the various ontologies is depicted in Figure 2 and is achieved through hard reuse via owl:imports. This approach allows the complete and unaltered reuse of the imported ontology (Poveda-Villalón et al., 2022). The OCQA ontology also includes trade-specific modules catering to task-specific inspection planning. For instance, the OCQA-screed extension encompasses all inspections related to the screed trade. The OCQA-TI will be developed as a trade-specific extension of the OCQA.

6.2 OCQA – Thermal Insulation (OCQA-TI)

This section overviews the OCQA-TI and the associated ontologies in detail. Therefore, the classes, relations, and properties needed to describe inspections related to the domain of thermal insulation appear in Figure 3. The top of Figure 3 illustrates the DiCon ontology and the main classes used as a basis to define the OCQA. The OCQA provides the general terminology to describe inspections, which the OCQA-TI will use to specify inspections for the trade of thermal insulation.

Representing all aspects of the thermal insulation inspection was essential to conduct it, including the actual inspections, the corresponding inspection plan, inspection equipment, personnel involved, inspection procedures, and inspection regulations through specific classes within the DiCon and OCQA ontologies, defined as subclasses of the DiCon ontology. The *ocqa:Inspection* class is a specialized subclass of *dicp:Activity* class, highlighting its unique role in the context of activities defined by DiCon.

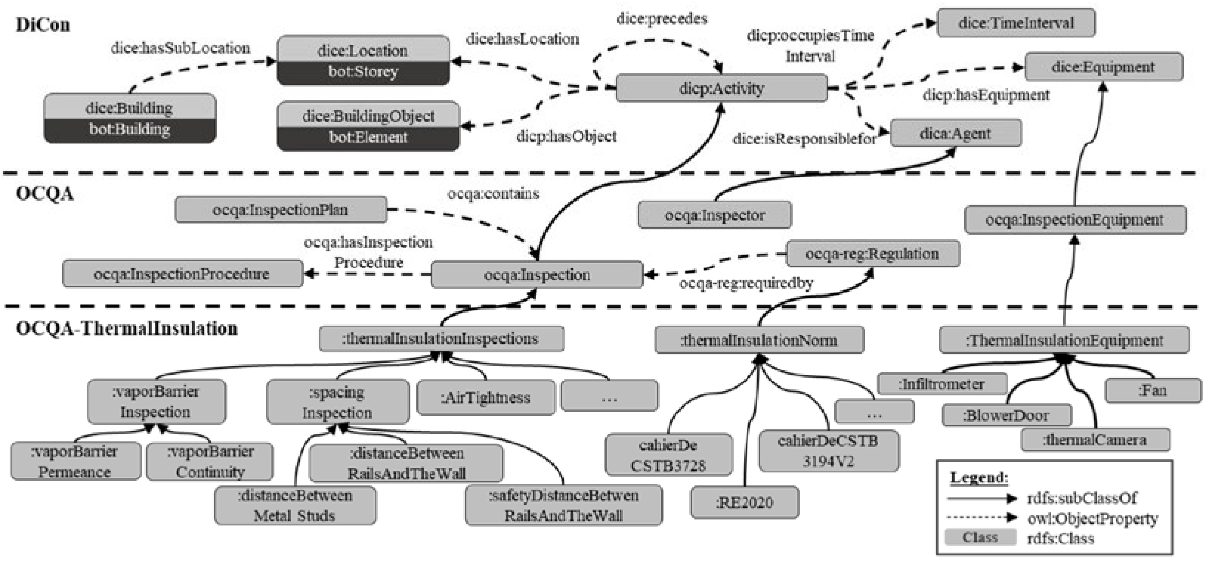

Fig. 3: Overview of classes, relations, and data properties of OCQA-TI and aligned ontologies.

The OCQA-TI is an ontology extension that enhances and refines the OCQA ontology, building on the DiCon ontology's foundational concepts. Within the OCQA-TI, the *:ThermalInsulationInspection* class represents various types of thermal insulation inspections like *:SpacingInspection*, *:AirTightnessInspection*, and *:VapourBarrierInspection* and is connected to the *ocqa:Inspection* class in the OCQA, signifying their specific role within the scope of quality inspections. Moreover, the *Inspection* class links to the *ocqa:InspectionPlan* class through the object property *ocqa:contains*, establishing a relationship between inspections and their inclusion in inspection plans. Additionally, *the ocqa:hasInspectionProcedure* object property connects the *ocqa:Inspection* class to the ocqa:InspectionProcedure class, specifying the procedures associated with each inspection. The *:ThermalInsulationNorm* class in the OCQA-TI, encompassing norms relevant to each thermal insulation inspection like RE2020, cahierDeCSTB3728, and cahierDeCSTB3194_V2 is introduced by the object property *ocqa-reg:requiredby,* which link this class to the *ocqa-regulation:Regulation* class.

Furthermore, the *:ThermalInspectionEquipement* class is introduced to describe the equipment required for thermal insulation inspections like *:ThermalCamera*, Infiltrometer, and *:BlowerDoor* and is directly linked to the *ocqa:InspectionEquipement* class in OCQA, which, in turn, is connected to the *dice:Equipment* class in the DiCon ontology, establishing a hierarchy of equipment concepts. Through these interconnected classes and object properties, the ontologies provide a comprehensive framework for managing and understanding thermal insulation inspections in the construction industry, utilizing construction quality assurance and workflows.

7. ONTOLOGY EVALUATION

The ontology evaluation is essential to check whether the developed ontology meets all the predefined requirements in the specification process (Fernández-López, M. et al., 1997). Different evaluation methods can be used to check compliance with different criteria (Zheng et al., 2021; El-Gohary and El-Diraby, 2010). This research evaluates the proposed OCQA-TI by automated consistency checking, CQs, and a task-based evaluation.

7.1 Automated Consistency Checking

Automated consistency checking aims to assess the developed ontology's consistency, guaranteeing no logical conflicts or inconsistencies. This process is achieved with description logic (DL) reasoners to assess the logical coherence of the ontology and maintain its integrity by ensuring there are no contradictions. Regarding the OCQA-TI, the automated consistency checking was conducted within the Protégé environment using the built-in Pellet reasoner. The automated consistency checking results showed that the OCQA-TI is consistent and coherent.

7.2 Answering the CQs and Task-Based Evaluation

We obtained practical inspection data from a residential building project about air tightness inspections, which are essential to ensure the condition of the air permeability before proceeding with the installation of thermal insulation. The assessment involved of implementing blower door tests while utilizing an infiltrometer as the specialized equipment to measure the value of the air permeability. The blower door tests were aligned with the stipulated guidelines of the RE2020 regulations, in which an air permeability constraint requires the measured value should be less than 0.6m3/(h.m3) for individual building types and 1m3/(h.m3) for residential building types.

The above example data was mapped and instantiated to OCQA-TI for two evaluation tasks. First, we used the instance data for answering the specified CQs. For the OCQA-TI, a SPARQL query was conducted to retrieve the target information of the thermal insulation inspection task to answer the example-specified CQs adapted from ontology CQs defined previously to check the coverage of the ontology. The CQs and results appear in Table 2. The results show that the OCQA-TI can retrieve accurate inspection information to answer the CQs, proving that OCQA-TI satisfies the ontology coverage criteria.

Second, based on the obtained data, we conducted a task-based evaluation to assess the usability of the proposed OCQA-TI ontology to solve a particular task. In this case, we conducted a use case to check if the measured air permeability values satisfied the RE2020 constraint. A SPARQL was conducted to identify the location where the air permeability value did not fit the constraint to provide the site manager with useful information to support awareness of the site condition and take actions to solve issues that occurred to ensure the upcoming tasks. The SPARQL query and result appear in Table 3. The result shows that the air permeability value in Zone B was 1.2, exceeding the maximum value in RE2020. Thus, the site manager should consider reducing the air permeability in Zone B to ensure the following insulation installation work. In summary of the task-based evaluation, the OCQA-TI can be used to check the inspection with the compliance of constraints from the norms.

Table 2: Specified CQs and answers based on the task of the blower door test.

Information retrieval	Answer
1. What are the characteristics being inspected by inspection :*Test001*?	*:AirPermeability _7832-3783-173*
2. What are related entities of an inspection?	
a. Where is the location of an inspection?	*:ZoneA*
b. Who is responsible for the inspection?	*:Inspector_XYZ*
c. What is the norm related to the inspection?	*:RE2020*
d. What equipment is required for an inspection?	*:NQ80YU64K*
3. What are following/precedence inspections of an inspection?	:*Test002*
4. Which procedure is required for an inspection?	*:BlowerDoorTest*
5. When is the start and end date of the inspection?	Start: *:04072023-1* End: *:04072023-2*

Table 3: SPARQL query and the result of air permeability constraint checking.

SPARQL query

```
SELECT ?test ?location ?value ?characteristic
WHERE {
  ?inspection a ocqa:Inspection .
  ?inspection ocqa:hasSubInspection ?test .
  ?test dicp:hasLocation ?location .
  ?location :hasAirPermeability ?characteristic .
  ?characteristic ocqa:hasAssignedCharacteristicValue ?AssignedCV .
  ?AssignedCV :maxvalue ?maxvalue .
  ?characteristic ocqa:hasActualCharacteristicValue ?ActualCV .
  ?ActualCV :value ?value .
  FILTER (?value > ?maxvalue)
}
```

Result illustrated in GraphDB

	test	location	value	characteristic
1	:Test002	:ZoneB	"1.2"^^xsd:double	:AirPermeability_7832-3783-174

8. CONCLUSION

In conclusion, poor construction quality remains a significant challenge in the construction industry, leading to increased costs and avoidable damage. Therefore, this paper proposed an innovative solution by developing the OCQA-TI. This ontology extension was designed to tackle the complexities of inspection planning and evaluation in thermal insulation and enhance the overall quality assurance process.

The research successfully extended the OCQA to incorporate thermal insulation, allowing for the description of insulation inspections and finishing trades. By bridging the gap between required and actual inspections on construction sites, the ontology provided proper knowledge, semantics, and terminology specific to thermal insulation, supporting inspectors and project teams in making informed decisions during an inspection. Additionally, the ontology facilitated gathering and integrating heterogeneous data from various software applications, promoting the traceability of information between systems. It also offered a practical solution for handling conflicting product guidelines, allowing references to guidelines instead of norms, thereby ensuring dual compliance with specific product requirements and regulatory norms.

This ontology development is expected to significantly improve construction site quality by enabling proactive defect prevention and enhancing the efficiency of inspection planning. With comprehensive and project-specific inspection plans readily available, construction teams can reduce the impact of work by better adhering to the inspection plans and rectifying any issues promptly. However, while the OCQA-TI ontology presents a valuable contribution, no ontology can be considered the definitive or best solution. As construction practices, regulations, and technologies evolve, continual improvement and updating of the ontology will be necessary to maintain its effectiveness.

Admittedly, there are several limitations of this study which are summarized as follows. First, the proposed ontology-based approach of thermal insulation inspection planning relies on the construction domain knowledge such as norms, standards, and production codes, which may be different in different regions or countries. For example, in this research, we adopt RE2020 to model the constraints, which is the French regulation that may not be applied to other countries. Therefore, to improve the usage of OCQA-TI globally, further efforts are needed to collect more international domain knowledge into the ontology. However, it is difficult to achieve by a single research team. Thus, in the future, we are aiming to provide a shared knowledge platform based on the OCQA-TI to collect more comprehensive knowledge for inspection by interaction and collaboration of users in different countries. Second, ontology needs to be continuously updated and maintained corresponding to changes of the domain knowledge and accommodating new inspection procedures, equipment, and reference values. Third, the ontology has not been fully applied or utilized on construction sites. Therefore, future research may expand the ontology to cover additional construction trades, enabling a comprehensive and interconnected quality assurance framework for various construction activities. Moreover, investigating automated inspection planning for the OCQA-TI using rule languages or other advanced technologies could further enhance the ontology's usability and efficiency. Additionally, there is the challenge of testing these technologies on a construction site in a real-world context, while also considering the socio-economic implications for construction workers and inspectors.

Overall, the OCQA-TI ontology offers a knowledge-driven approach to thermal insulation inspection planning, promoting enhanced information retrieval and data integration while supporting quality assurance decisions. By enabling early defect detection and addressing implementation issues, the ontology contributes to improved energy efficiency, interior comfort, and reduced building maintenance costs. As the construction industry continues to evolve, adopting such knowledge-driven approaches is crucial for ensuring safer, more durable, and energy-efficient buildings in the future.

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AN AUTOMATED FRAMEWORK FOR ENSURING INFORMATION CONSISTENCY IN PRICE LIST TENDERING DOCUMENT

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ABSTRACT: *Effective cost estimation for tendering plays a critical role in the building construction process, enabling efficient investment management and ensuring successful execution of the construction phase. Traditional cost estimation procedure involves manual information processing to extract and match technical data from textual description construction resources. This activity requires practitioner deep experience and manual effort, often resulting in errors and, in the worst scenario, judicial disputes.*

In response to the increasing demand for structured information and automated processes, this study addresses the need for Public Administrations to achieve better control over the data contained in public tendering documents provided to practitioners. To fulfill this objective, a framework is proposed to automatically retrieve information from these documents, serving as a support tool to map items within the documents, highlight missing data, and critical semantic ambiguity.

The designed framework aims to develop a tool for automatically identifying similarities between work items and their corresponding elementary resource items in Price List tendering documents. By leveraging the information retrieval NLP technique of cosine similarity through TF-IDF, a methodology was developed to support and facilitate practitioners' activities. Finally, the framework was tested on four case studies extracted from Lombardy Regional Italian price list documents showing that the resulting support tool is able to automate the analysis process and efficiently reveal inconsistency. The model successfully extracted and correctly matched the elementary resource to the corresponding work query in 75% of the cases where the elementary resource was present in the list. Additionally, the model proved to be a valuable tool in helping practitioners identify missing resources.

KEYWORDS: *Automated cost estimation, Information retrieval, Text similarity, NLP, Tendering document, Public Administrations*

1. INTRODUCTION

Cost estimation plays a pivotal role in effective decision-making within construction project management. Numerous studies underscore its significance (M.E.Sepasgozar et al., 2021). However, traditional construction cost estimation often involves multiple manual processes, with limited automation, resulting in time-consuming efforts and susceptibility to human errors (Akanbi & Zhang, 2021). Despite the increasing use of BIM approaches, information exchange in AEC industry is still mainly based on the production of paper-based documents. These documents are often written in natural language, conveying knowledge through unstructured or semi-structured data. Natural language is by nature unstructured, and it is therefore difficult to be digitally managed. Manually data extracting can lead to discrepancies and inaccuracies in information, thereby posing financial risks, project delays, potential failure, and in the worst case scenario to judicial disputes (Jafari et al., 2021a). These issues impact the effectiveness of the projects along with the credibility/reputation of the stakeholders. Moreover, the gap between traditional document-based (i.e., semi-structured and unstructured) and model-based information can lead to information loss and inconsistency. (Opitz et al., 2014). Thus, effective data management turns out to be essential to the overarching project strategy.

Public administrations play a key role in the construction process, especially in the context of public procurement where they assume the role of contracting authorities. These entities encounter a large daily influx of data, much of which needs to be made accessible to external stakeholders. Among these diverse datasets, a significant portion consists of unstructured textual information. Consequently, there is a need for these administrations to enhance their data management capabilities.

Effectively addressing these challenges necessitates the adoption of a methodology capable of efficiently handling and structuring the considerable volume of semi-structured and unstructured data for tasks such as cost and time estimation. Within this framework, data pre-processing emerges as a fundamental phase, acknowledged for its role as the most time-intensive aspect of text classification.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Chiara Gatto, Maryam Gholamzadehmir, Marta Zampogna, Claudio Mirarchi, Alberto Pavan, *An Automated Framework for Ensuring Information Consistency in Price List Tendering Document,* pp. 837-847, DOI 10.36253/979-12-215-0289-3.83

To address the aforementioned issues, and to meet the growing demand for public administrations and practitioners to convert textual information into digital formats, this research proposes a methodology to develop a procedure for checking information consistency within price list tendering. This is achieved through the application of Natural Language Processing (NLP) techniques, ensuring the coherence of information within the document. The methodology focuses on confirming the alignment between work descriptions and the employed elemental resources. The proposed research activity follows the prior study focused on automating the process of structuring data from textual documents (Gatto et al., 2023). Specifically, this research shifts the focus on responding to the public administration's need to assess the consistency of information within the regional price list before structuring and subsequently providing it to the user, by verifying the correspondence between the textual information related to the construction works and the textual information of the respective elementary resources involved.

To minimize semantic ambiguity and enhance machine comprehension without human intervention, data in textual documents can be handled using NLP, which has demonstrated its efficacy in supporting human activity (Zabin et al., 2022). In this direction, (Tang et al., 2022a) developed NLP and rule-based algorithms to automate the information extraction from work descriptions in building construction. They integrated different algorithms such as Hidden Markov model and improved the accuracy by 89% compared to other common named entity recognition algorithms. However, despite the wide application of NLP in different construction fields, the application of these techniques in the pre-design phase is still a research gap in the literature (Locatelli et al., 2022). Data pre-processing of unstructured data is known as the most time-consuming phase of text classification in the whole process (Munková et al., 2013).

This research is organized as follows: The initial section, "State of the Art," presents the research background. Following that, the "Research Methodology" and "Framework Development" sections detail the study's approach and implementation. The subsequent segments, "Testing Framework" and "Results and Discussion," demonstrate the practical application of the framework and its evaluation. Ultimately, the "Conclusion" section encapsulates the key findings from the study.

2. STATE OF THE ART

Manual extraction of reporting requirements from extensive construction documents can lead to time and cost underestimations. In this direction, the application of NLP techniques has been increasingly adopted in the AEC sector to manage the information contained in documents ((Jafari et al., 2021b); (J. Zhang et al., 2020)). NLP is mainly applied in four scenarios of information extraction, document organization, expert systems, and automated compliance checking (Wu et al., 2022).

Recently, NLP has been used in the construction industry to facilitate cost estimation through document management (Tang et al., 2022b). To automate extracting information from construction regulatory documents, a study has been developed by applying a semantic rule-based NLP approach for a text recognition algorithm based on semantic analysis (J. Zhang & El-Gohary, 2016). In a later study, an automated framework was developed using NLP and machine learning techniques to automatically recognize and prioritize important contract terms, enabling managers to quickly and fully understand contract agreements (Hassan & Le, 2020). Furthermore, a model that automatically identifies the most relevant pairs of provisions from various specifications using semantic text similarity was developed (Moon et al., 2021). This assists practitioners by reducing the effort to complete tasks that involve written documents, enhancing the objectivity of outcomes, and minimizing human errors.

In the construction industry, dealing with inconsistent information, semi-structured and unstructured data in price list documents is an ongoing challenge. The causes of these issues often include human errors during data entry, outdated price lists, and issues with the software tools used for creating BIM models and price lists (Cha & Lee, 2018). These issues can cause inaccurate cost estimates, budget overruns, delays in project timelines, and disagreements between project stakeholders.

Concerning the inconsistency and ambiguity checking, a recent research activity has been performed using the support vector machine (SVM) supervised learning model methodology, leading to an automated method for detecting ambiguity in building requirements, which can then be reviewed and interpreted by domain experts to support the automated compliance checking process (Z. Zhang & Ma, 2023). In another work, the authors proposed an uncertain knowledge graph-based method to eliminate potential conflicts and acquire the 'most likely scenarios' by integrating multiple representations of building information (Xie et al., 2023).

Document classification is crucial in the process of digitizing and structuring information. Text data pre-processing serves as a foundational step for this process (Lee & Yi, 2017). Text classification as part of NLP, involves the automated categorization of text. This task can be accomplished using two main approaches: rule-based techniques and Machine Learning (ML) algorithms.

The conversion of textual information into digital formats is necessary for the building tendering process. The digitalization process not only enhances the accessibility and usability of the information but also opens up new scenarios for data analysis and decision-making. Application of advanced technologies such as NLP and machine learning, can automate the structure of price lists and show similarities between products and their corresponding resource items. This can help practitioners improve the consistency of information in documents.

2.1 Research gaps and challenges

As the construction industry continues to embrace digital transformation, the application of NLP has emerged as a promising area of research. NLP has the potential to revolutionize various aspects of construction, from project management to BIM. However, the integration of NLP into the construction sector faces some challenges that are explained in this section to highlight future research interests in this field.

(Ding et al., 2022) provided a review of the NLP-related research articles in the construction field and they pointed out related challenges such as data accessibility/monopoly to develop the intelligent agent and data diversity from various devices, such as text, images, sensors, and audio, presenting a challenge in developing comprehensive models with higher performance. Additionally, they mentioned that achieving full automation and high-level reasoning requires advanced extraction and understanding of models because NLP models can struggle with understanding the complex technical context in construction.

Another challenge is achieving semantic interoperability between BIM and NLP in the construction industry. The use of ontology as a bridging tool is a potential solution to address this gap, yet this area remains underexplored (Locatelli et al., 2021).

2.2 Tendering documents

Tender documents serve as a communication tool between the project owner and potential contractors, outlining project specifications, execution conditions, and the rights and obligations of all parties. The clarity of these documents is important to avoid financial disputes. The type of tender documents depends on the procurement method and contract type, and typically include drawings, specifications, and bills of quantities (Cunningham, 2015).

The quality of tender documentation can significantly impact on the procedure, alongside other factors like contract content and tender management. Despite the challenges, contractors must carefully prepare their bids to increase their chances of securing the contract (Leśniak & Janowiec, 2020).

Construction projects, seen as transient businesses, require careful project management, particularly during the tendering process. This process, which involves numerous variables and substantial resources, is influenced by factors such as the financial stability of contractors, offered price, delivery timeline, experience, environmental considerations, and personnel qualifications (Naji et al., 2022).

The Public Italian Contracts Code, art.23 D.lgs 18 Aprile 2016, n.50, imposes on each Italian region to annually provide a price list that contracting authorities have to use for setting the project cost base for tenders. Therefore, each region provides practitioners with a price list containing work items and their respective cost (Sdino & Rosasco, 2021). The tool mainly stores data associated with construction activities, including their unit prices. This resource assists practitioners in generating estimated metric calculations. Additionally, to ensure more transparency in the composition of the price of construction works, the price list provides a catalog of elemental resources involved in the latter. Therefore, there must be a full correspondence between works and elemental resources, otherwise inconsistency arises. Considering the need for annual updates, the price list is subjected to periodical revisions, consisting in the unit prices update, the addition of new work and elementary resource items or removal of outdated entries.

Information is conveyed by the tool in verbal form: sentences composed by words and syntax delivering knowledge. Since each item is written in natural language and because the document doesn’t follow a standard in providing information, a lack of homogeneity has been recorded between each item phrase structure and information typology transmitted. Public Administrations therefore are looking for tools to help them structure high amount of data.

3. RESEARCH METHODOLOGY

The methodological approach employed in the presented study is explained in this section and summarized as depicted in Figure 1Figure 1 Methodology chapter. Firstly, the development of the study starts by listening to the needs of public administrations in the AEC sector, who have been engaged to comprehend the challenges they face in managing information during public tendering processes. Following the prior study focused on automating the process of structuring data from textual documents (Gatto et al., 2023), a need emerged from public administrations to incorporate a preliminary step to assess the consistency of information within the regional price list before structuring and subsequently providing it to the user. The subsequent step was to explore the state of the art, aiming to delve into tools and methodologies applied for automating the management of unstructured data. This was followed by the development of a framework, leveraging information retrieval NLP techniques. Specifically textual similarity recognition based on cosine similarity using TF-IDF, was selected to build a tool designed to aid public administrations in establishing associations among essential resources within a construction project, thereby highlighting any gaps that may exist. This technique has proved to be valuable and effective within the domain of text similarity and in this study it is applied in the specific field of cost estimation, focusing on price list documents. Finally, the framework was tested in a practical case study to assess its effectiveness.

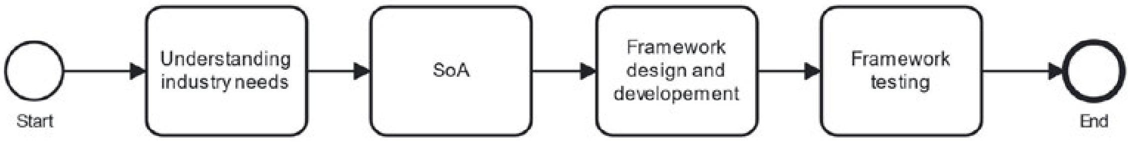

Figure 1 Methodology chapter.

4. FRAMEWORK DEVELOPMENT

This section presents the design and development process of the framework, as synthesized in Figure 2. The objective of this phase is to develop a comprehensive procedure for checking information consistency within price list tendering documents using Natural Language Processing (NLP) techniques, specifically aimed at verifying the correspondence between the textual information related to the construction works and the textual information of the respective elementary resources involved. The primary goal of public administrations is to provide users with a tool that ensures utmost clarity, free from semantic ambiguities and inconsistencies during the crucial phase of estimating construction costs.

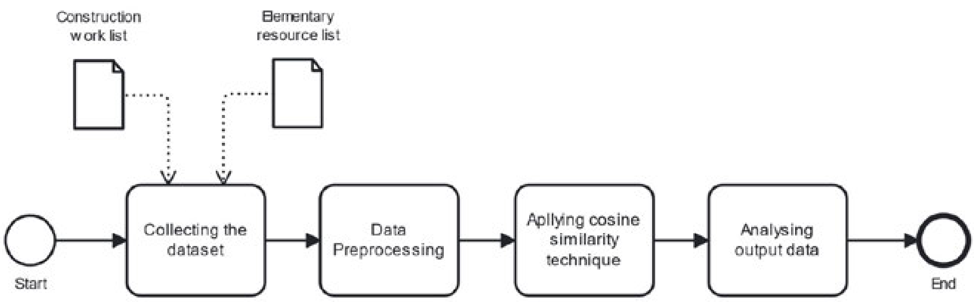

Figure 2 Framework flowchart.

By leveraging NLP technique, this framework allows the public administration to speed up the process of addressing elementary resource item to the work items where it is involved, thus helping with the detection of missing information and inconsistencies, ensuring the accuracy and reliability of how the data is presented to the user. The parameterization of information through NLP techniques empowers public administrations with greater control over the textual dataset, facilitating easier data manipulation and analysis. Furthermore, this process seeks to address the longstanding issue of ambiguity that often arises from cost item descriptions, ensuring a higher level of accuracy and precision in subsequent analyses and decision-making processes.

The developed framework mainly consists of four stages.

The first step in the process involves collecting the dataset, which comprises both the list of completed works and the corresponding list of elementary resources involved. The work's textual descriptions typically explicitly state the elementary resources utilized in the activity, allowing practitioners to identify them accurately. Once the dataset is assembled, it undergoes a pre-processing phase to ensure the correct execution of the subsequent steps.

Since the description of the elementary resources is expected to be contained in the description of the works, the cosine similarity technique using TF-IDF is chosen for the development of this framework. This measures the similarity between two vectors, A and B, by calculating their dot product and dividing it by the product of their magnitudes as:

$$(|A||B| * \cos(\alpha))/(|A||B|)$$

The resulting value ranges between 0 and 1, where 0 indicates no match (completely dissimilar vectors), and 1 represents complete similarity (vectors pointing in the same direction). This metric is widely used in text analysis to measure document similarity. TF-IDF is primarily concerned with determining the importance of words within individual documents and in literature is commonly used for tasks like information retrieval and document ranking, and in text. Alternatively, the utilization of cosine similarity through Word2Vec is centered around capturing semantic meanings. This is achieved by representing each word as a dense vector within a continuous space. Notably, certain studies have suggested that for text similarity, TF-IDF often outperforms the other method, highlighting its effectiveness (Sitikhu et al., 2019).

Once the dataset has been collected and the NLP technique to be used identified, the next step is to vectorize the list of elementary resources dataset and query them with the respective work descriptions, with the aim of deriving the elementary resource item associations. The cosine similarity technique allows to rank the list of elementary resources based on their similarity to the work descriptions, with the most similar resources being assigned with higher score similarity value.

After obtaining a ranked list of elementary resources associated with each work description, building construction cost estimation practitioners were involved to validate the accuracy and effectiveness of the output results. They carefully reviewed the output and assessed whether the correctness of the output with a higher score rate. The expert validation process not only serves as a critical quality control measure but also provides valuable insights and feedback, enhancing the overall robustness and practical applicability of the framework.

5. TESTING FRAMEWORK

In this section, the testing process of the framework is presented, with the aim of assessing its capability to accurately determine the appropriate elementary resource for each work item. The evaluation was conducted using four sample case studies extracted from the Lombardy Region Price List document (January 2023 version). The objective was to verify the framework's ability to assign the correct elementary resource to four specific types of works: masonry clay block, masonry concrete block, tile floor, and thermal insulation work.

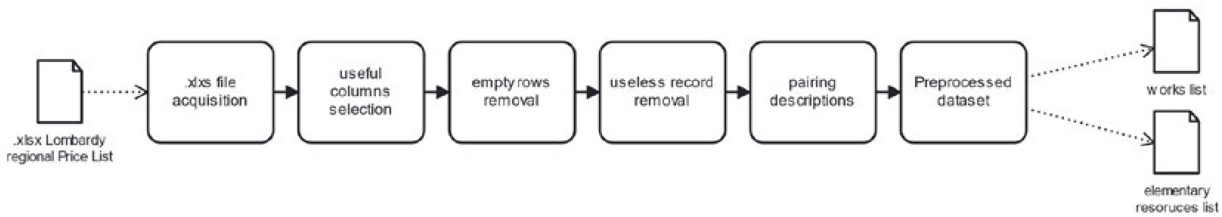

Figure 3 Preprocessing flowchart.

To ensure effective vectorization and handling of relevant information, dataset pre-processing plays a crucial role. The steps undertaken during this phase are depicted in Figure 3. As explained later, the pre-processing is focused on isolating and extracting the pertinent textual data; however, it does not involve further cleaning, such as removing stop words or those that appear with high or limited frequency in the text. The objective is to retain the essential context and meaningful information while preparing the data for vectorization and subsequent analysis.

Data was acquired from a single spreadsheet. where the knowledge organization follows a semi-structured format as shown in Figure 3, consisting of seven columns in the following order: item ID code, textual description, unit of measurement, unit price, percentage of labor incidence, percentage of material incidence, and percentage of equipment incidence.

CODICE	DESCRIZIONE	U.M.	P.U.	% Inc. M.O.	% Inc. MAT	% Inc. ATT
1C.06.100	MURATURE FACCIA A VISTA	NaN	NaN	NaN	NaN	NaN
NaN	NaN	NaN	NaN	NaN	NaN	NaN
1C.06.100.0050	Muratura faccia a vista con mattoni pieni tipo ...	NaN	NaN	NaN	NaN	NaN
NaN	NaN	NaN	NaN	NaN	NaN	NaN
1C.06.100.0050.a	- con mattoni 25 x 12 x 5.5 cm, spessore 12 cm	m²	98,31	33,90	41,38	NaN
NaN	NaN	NaN	NaN	NaN	NaN	NaN
1C.06.100.0050.b	- con mattoni 25 x 5.5 x 5.5 cm (bastonetto), ...	m²	88,99	36,52	40,52	NaN
NaN	NaN	NaN	NaN	NaN	NaN	NaN
1C.06.100.0100	Muratura faccia a vista con mattoni semipieni ...	NaN	NaN	NaN	NaN	NaN
NaN	NaN	NaN	NaN	NaN	NaN	NaN

Figure 4 Raw dataset.

The raw dataset is characterized by many rows with null records, therefore, after the acquisition of the Lombardy Regional Price List document, the first step performed for cleaning the dataset is the removal of empty rows. Subsequently, only the useful columns have been selected, containing the ID code information and textual description of items.

Moreover, the hierarchy knowledge of information, such as chapters and sub-chapters, is provided by the price list tool by code length. The shorter the code, the higher is the hierarchical level of information; conversely, the longer the code, the deeper is the hierarchical level of information transmitted. In Figure 4, the first record characterized by the code "1C.06.100" represents the chapter referring to the exposed brick wall works, while the records with longer codes are the specific work activity within the masonry chapter. For the achievement of the objectives set within this paper, the data type to work with belongs to the last hierarchical level, where data are conveyed with the highest level of detail through textual items description. Work and elementary resource descriptions which a unit price is associated with are characterized by a code length higher than 13 digits.

Since elementary resources could be described at both single code and parent-child code levels, the last pre-processing step involved pairing the child entries with their respective parent entries, ensuring the framework's accuracy in resource assessment, as shown in Figure 5, where the process of pairing items description is shown.

By following these steps, we ensured that only relevant and properly organized data were used in the testing process, further validating the framework's effectiveness in elementary resource allocation for construction works.

The following stage consists of the cosine similarity technique application. Scikit-learn library have been used for

```
('MC.06.050.0025', 'Exposed bricks 6 x 11 x 23 cm sandblasted'),
 ('MC.06.050.0030', 'Semisolid exposed bricks:'),
 ('MC.06.050.0030.a', '- brick 25 x 10 x 5.5 cm'),
 ('MC.06.050.0030.b', '- brick 25 x 10 x 10 cm'),
 ('MC.06.050.0030.c', '- brick 25 x 12 x 5.5 cm'),
 ('MC.06.050.0030.d', '- brick 25 x 12 x 7 cm'),
 ('MC.06.050.0030.e', '- brick 25 x 12 x 10 cm'),
 ('MC.06.050.0030.f', '- double UNI 25 x 12 x 12 cm')
```

```
['MC.06.050.0025', 'Exposed bricks 6 x 11 x 23 cm sandblasted'],
 ['MC.06.050.0030.a', 'Semisolid exposed bricks:- brick 25 x 10 x 5.5 cm'],
 ['MC.06.050.0030.b', ' Semisolid exposed bricks:- brick 25 x 10 x 10 cm'],
 ['MC.06.050.0030.c', ' Semisolid exposed bricks:- brick 25 x 12 x 5.5 cm'],
 ['MC.06.050.0030.d', 'Mattoni semipieni faccia a vista:- brick 25 x 12 x 7 cm'],
 ['MC.06.050.0030.e', 'Semisolid exposed bricks:- brick 25 x 12 x 10 cm'],
 ['MC.06.050.0030.f', 'Semisolid exposed bricks:- double UNI 25 x 12 x 12 cm']
```

Figure 5 From left to right, the process of pairing child entries with their respective parent entries.

this purpose importing in a Google Colab notebook the *TfidfVectorizer* class and using the function *cosine_similarity*.

Descriptions from the elementary resource list are converted from textual to numerical representation through TF-IDF feature extraction action, obtaining a sparse matrix. This process effectively maps the vocabulary of the dataset's domain knowledge. As a result, each phrase in the dataset is transformed into a vector within the TF-IDF feature space, representing its unique characteristics in relation to the entire corpus of documents.

Later, the same process is repeated for a single description query, which comes from the works list. This query is transformed into a TF-IDF feature vector using the *TfidfVectorizer* that was fitted on the product descriptions.

Finally, the *cosine_similarity* function calculates the similarity between the query and all records (product descriptions) in the product list. This provides a similarity score for each elementary resource within the list with respect to the query. The products characterized by the most similar description to the query are retrieved by sorting the similarity scores in descending order, from the highest to the lowest value. For this study, it was decided to recall only the first 5 products, leaving out the later ones.

In the table below it is shown an example of the framework, by querying the list of products with the “1C.06.050.0100” work, whose description is “Semi solid masonry wall, 8 x 12 x 24 cm, with cement mortar, including the charge for the formation of shoulders, vaults, corners, pilasters, internal worktops”. The first elementary resource returned by the proposed methodology is the correct characterizing product of the enquired work. The overall proposed framework exploits cosine similarity through TF-IDF techniques for retrieving products in the Price List document. Those are ranked based on their similarity scores, allowing the user to identify the most relevant matches for the query.

The framework is tested on four samples. Each sample represents a different domain (masonry clay blocks, masonry concrete blocks, tile floors, and thermal insulations) with unique terminologies and sentence structures. By testing the developed methodology on a diverse dataset, it is possible to assess its scalability on different knowledge subdomain.

The last step of the framework requires the evaluation of the output, performed by practitioners, who assesses the correctness of the first output, characterized by the highest score rate.

Table 1 Framework output, queried with “1C.06.050.0100” work.

Score rate	ID code	description
0.50	MC.06.050.0040.a	Semi-solid bricks:- semisolid brick 8 x 12 x 24 cm
0.43	MC.06.050.0040.b	Semi-solid bricks:- semisolid brick 8 x 24 x 24 cm
0.38	MC.06.050.0040.e	Semi-solid bricks:- double UNI semi-solid brick 24 x 12 x 12 cm
0.34	MC.06.050.0045.c	Semi-solid bricks complying with UNI EN 771-1 and the Minimum Environmental Criteria set forth in the Decree of 23 June 2022 of the Ministry of Ecological Transition, for the construction of partitions or counterwalls; type - dimensions (length x width x height) in cm - perforation (%<) - thermal conductivity (λ) according to UNI 1745 of dry brick - fire resistance with normal and fireproof plaster* - soundproofing power:- block with horizontal holes 30x4.5x15 cm - dB 39
0.33	MC.06.050.0015	Solid bricks 25 x 12 x 5.5 cm complying with UNI EN 771-1 and the Minimum Environmental Criteria set forth in the Decree of June 23, 2022 of the Ministry of Ecological Transition, for the construction of load-bearing masonry according to NTC 2018, thermal conductivity (λ) according to UNI 1745 of dry brick 0.431 W/mK

6. RESULTS AND DISCUSSION

In this section, a preliminary phase of analysis and discussion of the analyzed dataset is presented. This approach allows us to have a more comprehensive view of the results obtained before delving into further discussions.

6.1 Dataset preliminary analysis

A preliminary analysis was performed in order to provide a better description and visualization of the four selected dataset. Table *1* collects some significant data on which the evaluations are performed. It provides the size of the tested sample, both for works and elementary resources, for the subdomain knowledge analyzed (Clay brick wall, concrete brick wall, tiles, and thermal insulation). Furthermore, it provides the description with major, minor, and average number of words per work and elemental resource. A delta is also given to highlight the differences between works and elemental resources.

As it is possible to see from the table below, a homogeneous number of 40 work items have been analyzed for each test campaign. The related number of elementary resources varies according to the type of knowledge subdomain, ranging from a minimum of 33 to a maximum of 64 items.

Concerning the analysis of textual descriptions, the number of words in them was investigated. The clay Brick Wall campaign is characterized by 50.8 average words per work item. and 30.7 average words per elementary resource item, registering a delta of 20.1 words. Among the test campaigns, the Concrete Brick Wall campaign stood out with the longest descriptions, averaging 123.9 words per work item. In contrast, the Elementary Resources campaign displayed a mean word size of 59.9, exhibiting the largest word delta between the two.

The Thermal Insulation test campaign also featured lengthy descriptions. In this case, the average word count for both elementary resources and jobs was quite similar. On the other hand, the Tile Floors knowledge subdomain had the shortest textual descriptions for both elementary works and resources; moreover, the average length of the descriptions for works and elementary resources nearly matched, resulting in an almost zero delta.

Based on this overview, it is evident that there are differences among the various knowledge subdomains. Specifically, the Concrete Brick Wall subdomain requires a greater number of words to convey information. Additionally, the descriptions of works within this subdomain offer more extensive information compared to their corresponding elementary resources. Conversely, the Tile Floor subdomain necessitates fewer details in its descriptions, with both works and elementary resources providing relatively concise information. These differences highlight the varying informational needs and content richness across the different knowledge subdomains.

Table 2 Preliminary dataset analysis. W: work items; ER: elementary resource items.

	Clay brick wall			**Concrete brick wall**			**Tile floor**			**Thermal insulation**		
	W	ER	Δ	W	ER	Δ	W	ER	Δ	W	ER	Δ
.n° of items	*40*	*33*	*7*	*40*	*50*	*-10*	*40*	*59*	*-19*	*40*	*64*	*-24*
Max length	*105*	*89*	*16*	*140*	*121*	*19*	*82*	*94*	*-12*	*150*	*121*	*29*
Mean length	*50.8*	*30.7*	*20.1*	*123.9*	*59.9*	*64*	*46.3*	*46.5*	*-0.2*	*85.6*	*98.1*	*12.5*
Min length	*13*	*10*	*3*	*54*	*28*	*26*	*10*	*10*	*0*	*49*	*33*	*16*

6.2 Discussing framework result

Table 4 in this paragraph presents the results obtained, by displaying in the first row the number of times the model successfully assigned the elementary resource to the work query. Conversely, in the second row, the table shows the number of times when the model was unable to assess the correct output. The last row provides the number of missing elementary resource items. According to the domain of knowledge, different outcomes were achieved.

The poorest results were recorded for the Concrete Brick Wall and Clay Brick Wall domains. Also, as previously shown in table 3, these domains exhibited a substantial delta between the number of words between works and elementary resources, indicating that the works conveyed more information than the descriptions of elementary resources. For the Clay Brick Wall sample, 19 tests over 40 provided incorrect output, being 47.5% of the total tests; however, practitioners verified that in the 57.8% of incorrect outputs, the elementary resource is missing in the price list. Concerning the Concrete Brick Wall sample, 26 tests over 40 provided incorrect output. being 65% of the total tests.

Furthermore, it was observed that in certain instances, standardizing works and elementary resources resulted in a shift from negative to positive outcomes. Table 3 shows the output of the work query “Load-bearing masonry made of hollow core brick blocks, thermo-acoustic, with cement mortar, including formation of vaults, pilasters, corners; with:- simple blocks 13 x 30 x 19 cm, thickness 13”. The model does not return the correct elementary resource as the first output, but rather as the third ranked output. Just by equalizing the lexicon from "block" to "blocks", like the other items are, the similarity score of the correct output turns from 0.37 to 0.44, with a higher score.

Table 3 Framework output, queried with "1C.06.050.0300.b" work.

Score rate	ID code	description
0.39	MC.06.100.0010.b	Thermal insulation blocks, 45% drilling:- interlocking blocks, 30 x 25 x 19 cm
0.39	MC.06.100.0010.a	Thermal insulation blocks, 45% drilling:- interlocking blocks, 25 x 30 x 19 cm
0.37	MC.06.100.0010.c	Thermal insulation blocks, 45% drilling:- simple block, 13 x 30 x 19 cm

Conversely, Tile Floor and Thermal Insulation domains exhibited a larger number of positive outcomes, registering respectively 35 and 37 correct output tests out of 40, 87.5% and 92.5% respectively. In these cases, unlike previous tests, the descriptions of works and elementary resources had a smaller word delta. For Thermal Insulation, practitioners verified that in 67% of the negative outcomes, the correct data was indeed missing from the elementary resources list.

Table 4 Testing framework results.

	Clay brick wall	Concrete brick wall	Tile floor	Thermal insulation
correct	*21*	*17*	*35*	*37*
incorrect	*19*	*26*	*5*	*3*
Missing ER	*11*	*0*	*0*	*2*

7. CONCLUSION

The research presented in this study contributes to the empowerment of public administrations in effectively managing data from Price List Documents, aligning with the growing necessity to transition textual information into structured and machine-readable formats. Building upon the investigation conducted in the research titled (Gatto et al., 2023), this study introduces a methodology capable of extracting elementary resource information from a price list document and linking it to the corresponding construction work using cosine similarity NLP techniques.

The model successfully extracted and correctly matched the elementary resource to the corresponding work query in 75% of the cases where the elementary resource was present in the list. Additionally, the model proved to be a valuable tool in supporting practitioners in identifying missing resources. A limitation associated with this approach is its reliance on retrieving explicitly mentioned information from the text. Indeed, it cannot derive implicit information.

The study also highlighted that due to the lack of standardization in conveying information, the machine encountered ambiguity in interpreting the text. It emphasized the importance of adopting a more standardized approach to delivering information, making it more understandable not only to machines but also to humans.

It is important to note that the developed framework does not replace human activity but rather acts as a supporting tool. Human verification and validation of the model's outputs are essential.

Given the success of this framework, future developments aim to extend its application to broader contexts, with a focus on extracting cost information from various textual documents, including technical specifications and price list documents, and linking them to verify the consistency of cost information with the data contained in BIM models.

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ENHANCING INTERACTIONS IN AUGMENTED REALITY FOR CONSTRUCTION SITES: INTRODUCING THE ARCHI ONTOLOGY

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ABSTRACT: *Augmented reality (AR) systems offer new possibilities for enhancing how people interact with information and their environment in the construction sector. However, traditional software-driven approaches to AR system design have limitations in creating intuitive user experiences. This research presents a new user-centric framework and ontology for BIM-AR system development focused on human needs and perspectives. The BIM-AR Framework consists of a 5-step circular hybrid process with the user at the center. To enable knowledge sharing, the Augmented Reality Computer-Human Interaction (ARCHI) ontology was developed using Protégé based on established design principles. Initial validation indicates the framework's potential for improved AR system design, but further expert review and case studies are needed. The ontology also requires additional refinement and linkage to open data. This pioneering research lays the groundwork for next-generation AR systems that emphasize usability by taking a human-focused approach. With rigorous validation and evolution, the framework and ontology could transform AR technology development to create more purpose-driven and adopted solutions. This research represents a paradigm shift to user-centric AR system design that has significant potential to improve how augmented reality enhances construction project management.*

KEYWORDS: *Augmented Reality, Building Information Modeling, BIM, Linked Data, Ontology, Human Computer Interaction.*

1. INTRODUCTION

Augmented reality (AR) refers to technology that overlays digital information and objects onto the real-world environment in real-time (Azuma et al., 2001). This is achieved by supplementing the user's view with computer-generated input such as text, images, video, audio, and GPS data. In recent years, AR has emerged as a transformative technology with a diverse range of applications across industries like healthcare, education, manufacturing, and construction. Within the construction industry, AR is being explored as a means to enhance on-site work processes and information visualization. By overlaying 3D models, assembly instructions, or other data directly onto physical construction sites, AR enables workers to intuitively interact with digital information in context (Rankohi & Waugh, 2013). Specific applications include visualizing building designs and underground infrastructure, annotating issues for repair, remotely guiding workers through assembly tasks, and detecting risks or errors in construction (Behzadan & Kamat, 2009). AR and Building Information Modelling (BIM) can reduce workspace clutter, improve information communication, and integrate digital tools directly into the work environment (Um et al., 2023).

However, there are several challenges to widespread AR adoption in construction. Current AR solutions are often provider-specific proprietary platforms that lack interoperability (Um et al., 2023; X. Wang et al., 2013). This makes integrating AR into existing construction workflows difficult, as data may not transfer seamlessly between different vendor tools. Additionally, much AR research has focused on novel visualization techniques rather than task-based, user-centric design (Amin, Mills, & Wilson, 2023; Behzadan & Kamat, 2009). As a result, usability and practical utility for on-site workers requires further improvement. To drive end-user acceptance, AR solutions need to tie tightly to actual construction tasks and processes, with UX design centered around user needs (Rankohi & Waugh, 2013). Realizing AR's full potential in construction will require developing flexible and standardized AR platforms that can be tailored to diverse use cases. Rather than one-size-fits-all vendor products, open AR ecosystems are needed where components can be mixed and matched (K. Wang et al., 2023; X. Wang et al., 2013). Tying these tools directly to construction workflows and end-user requirements will be key. With improved integration and usability, AR can transition from isolated proofs-of-concept to transformative mainstream applications in construction.

2. BACKGROUND

In recent years, AR has emerged as a potentially transformative technology for the architecture, engineering, and construction (AEC) industry. By superimposing digital models, data, and instructions directly onto physical

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Karim Farghaly, Khalid Amin, Grant Mills, Duncan Wilson, *Enhancing Interactions in Augmented Reality for Construction Sites: Introducing the Archi Ontology,* pp. 848-855, DOI 10.36253/979-12-215-0289-3.84

construction sites and assets, AR enables more intuitive visualization and interaction with information in context. Researchers have explored AR applications across the construction lifecycle, including design visualization, construction planning, progress monitoring, quality inspection, maintenance, and safety training (K. Wang et al., 2023). One major area of research has been integrating AR with Building Information Modeling (BIM) to extend the utility of virtual BIM models to physical construction settings. BIM refers to digital 3D models of buildings containing rich parametric data on components and systems. Linking geo-located BIM models with AR allows contextually relevant on-site visualization and interaction with model data (Amin, Mills, & Wilson, 2023). This has been posited to improve communication, decision-making, work planning, quality control, and collaboration between on-site and off-site teams during construction and operations (Elshafey et al., 2020).

However, studies note that widespread field adoption of BIM-AR remains limited, especially in developing countries, due to technical and organizational challenges (Sidani et al., 2021). Major technical barriers include issues with accurate and stable registration of virtual content with the physical environment. This is impacted by factors like lighting, network connectivity, and occlusion (X. Wang et al., 2013). Developing flexible AR platforms that can leverage different positioning techniques based on context has been identified as important. Organizational challenges also exist around integrating AR into construction workflows and aligning it with user requirements (Amin, Mills, Wilson, et al., 2023). In particular, research gaps remain around understanding user needs and perspectives for on-site AR applications. As Amin, Mills & Wilson (2023) discuss, much AR research has focused on novel visualization techniques rather than task-based, user-centric design. However, usability and practical utility requires aligning AR tightly with actual construction tasks and end-user workflows. Wang & Dunston (2006) and K. Wang et al. (2023) similarly argue there has been insufficient investigation of user-centered factors that influence the effectiveness of AR for on-site construction tasks. These include aspects like UI design, functionality, and ergonomics based on workers' processes and needs.

Overall, studies emphasize that realizing the potential of BIM-AR in construction requires moving from proofs-of-concept to solutions tailored to end-users' requirements and field workflows. This entails research on AR applications within the context of specific construction tasks, roles, and information needs. A user-driven approach can help identify high-impact areas where AR adds value for field personnel and integrate AR seamlessly into existing construction practices and project delivery processes. Bridging these research gaps around user-centered design and task-based workflows will be key to driving user acceptance and widespread adoption of BIM-AR on construction projects. In the following section we will discuss the current practice of the implementation of BIM-AR solutions.

3. BIM-AR CURRENT PRACTICE

The typical process of developing and implementing BIM-AR solutions tends to follow a linear path (Figure 1), rather than a circular user-centric approach. Researchers/Project Managers often identify a potential construction application area for BIM-AR visualization, such as design review or progress tracking, based on technical feasibility rather than validated user needs (Amin, Mills, & Wilson, 2023). Developers then select AR hardware and software components to prototype, focusing on demonstrating novel visualization capabilities more than usability (X. Wang & Dunston, 2006). A pilot study is conducted to test the BIM-AR prototype in a lab or limited field setting, with evaluation criteria tending to be technical performance metrics rather than workflow integration or user-centered design (Sepasgozar et al., 2016). If feasible, the prototype may be deployed in a real construction project to showcase a “proof of concept”, but these deployments often function as stand-alone tools disconnected from broader workflows and BIM processes. User feedback is collected informally, if at all, and BIM-AR solutions are not co-designed with end users or iteratively refined based on their input and task needs. Outcomes focus on the technical aspects and visualization capabilities, rather than productivity, quality, or other construction industry benefits. Consequently, BIM-AR prototypes frequently stall at the proof-of-concept stage without translation into commercial solutions or best practices (K. Wang et al., 2023). In summary, the current linear BIM-AR development process does not start with identifying user requirements or aligning systems tightly to construction workflows. Collaboration with industry stakeholders occurs late, if at all, which limits the real-world utility and adoption of BIM-AR innovations. A more circular, participatory design approach is needed, where end user perspectives drive the development and evaluation of BIM-AR solutions for construction.

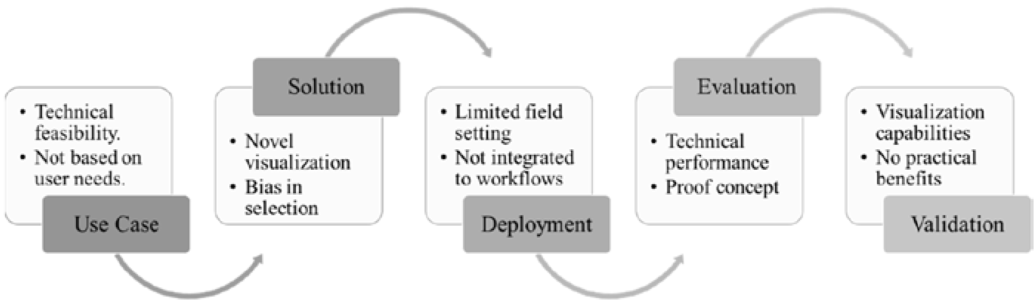

Figure 1: The current practice of BIM-AR solutions and research

4. PLUG&PLAY BIM-AR SOLUTION

A more circular approach for the effective implementation of BIM-AR solutions in the construction industry is proposed. As mentioned before, the current linear process of BIM-AR development has limitations, as it does not sufficiently incorporate end user requirements or align solutions with real-world workflows. To address this, we suggest a participatory, iterative process, Augmented Reality Computer-Human Interaction (ARCHI), that centers end user perspectives for (Figure 2):

- Cultivate Use Case - The starting point should be identifying a practical use case cultivated by end users. This includes details on the application area, project phase, location, and key stakeholders who would benefit from the BIM-AR implementation. Example use cases could be design coordination, construction planning, or facilities maintenance.
- Identify Requirements - With a target use case, multidisciplinary workshops with stakeholders are held to determine functional and information requirements. User requirements capture necessary features and workflows to efficiently accomplish tasks using BIM-AR. This entails understanding objectives, processes, pain points, and needs. Information requirements outline graphical and non-graphical data inputs from integrated systems like BIM to achieve the user requirements.
- Map to Key Functions - The user and information requirements are then mapped to key BIM-AR functions needed to fulfill the use case. As Amin, Mills & Wilson (2023) proposed, these functions include positioning, visualization, interaction, collaboration, automation, and integration. Not all functions are necessary; the focus is on those critical for the specific use.
- Select Solution - With key functions defined, the project team surveys potential AR devices, software platforms, and components to meet the requirements. Table 1 provides an overview of current BIM-AR solutions and capabilities. The goal is finding flexible tools to fulfill the required key functions.
- Implement with Users - BIM-AR experts collaborate with end users to implement the selected solution in the construction project context. Workshop sessions ensure it aligns properly with real-world workflows while addressing information needs. Agile development principles can help adapt the system based on user feedback.
- Assess Against Use case and Requirements - Once deployed, structured assessments evaluate the BIM-AR solution against the original functional and information requirements. Metrics quantify performance, usability, and impact on productivity, quality, safety, etc. User surveys also provide qualitative feedback on enhancements.

By applying this circular approach, BIM-AR solutions are driven by end user and project requirements rather than technical novelty. The focus is on integrating AR seamlessly into existing construction practices to solve real problems. Continuous assessment and improvement further refine the system over time and across projects. With BIM-AR tools tightly aligned to use cases and stakeholder needs, user adoption and benefits can expand markedly. This practical, participatory implementation process is key to unlocking the true potential of BIM-AR in construction.

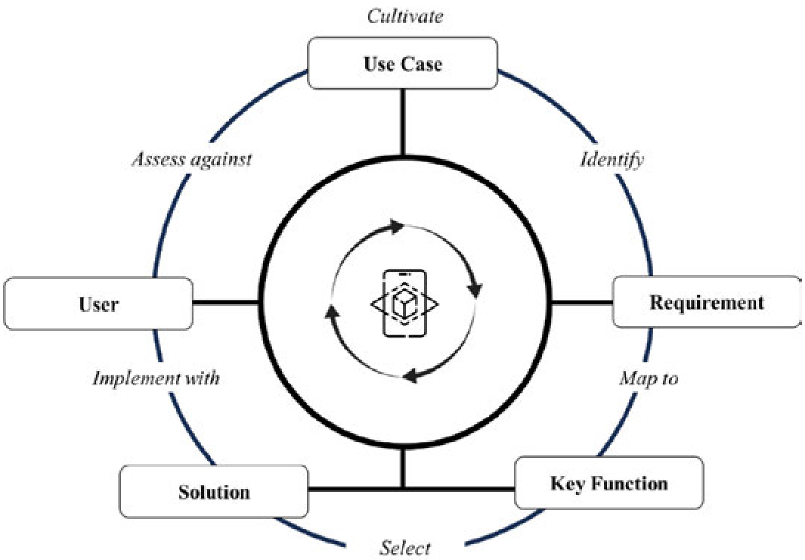

Figure 2: ARCHI proposed framework

Table 1: The existing solutions of BIM-AR (available in the construction market in 2023).

Solution	Hardware	Software	Type	User Interface
HoloLens-Kognitiv Spark	HoloLens	Kognitiv Spark	Headset	Gestural-based
Varjo XR-3	Varjo XR-3	-	Headset	Gestural-based
ATOM-XYZ Cloud Platform	ATOM	XYZ Cloud Platform	Headset	Tangible User Interface
iPad Pro-Gamma AR	iPad Pro	Gamma AR	Tablet	Touch-based
iPad Pro-GenieVision	iPad Pro	GenieVision	Tablet	Touch-based
iPad Pro-Augmentecture	iPad Pro	Augmentecture	Tablet	Touch-based
iPad Pro-ARKI	iPad Pro	ARKI	Tablet	Touch-based
iPhone -Gamma AR	iPhone	Gamma AR	Smart Phone	Touch-based
iPhone -GenieVision	iPhone	GenieVision	Smart Phone	Touch-based
iPhone -Augmentecture	iPhone	Augmentecture	Smart Phone	Touch-based
iPhone -ARKI	iPhone	ARKI	Smart Phone	Touch-based

5. ARCHI ONTOLOGY

To achieve the proposed framework, it is crucial to identify and capture all the key information needed for effective implementation. In this section, we introduce the ARCHI ontology which identifies all the important aspects to be captured. For developing a domain or upper ontology, it is essential to follow a set of defined recommendations and ordered steps (Farghaly et al., 2023). The process of the development of an ontology consists of seven main steps (Noy & McGuinness, 2001). The first step is to define the covered domain and the scope. As mentioned before, this research concentrates on the aspects related to BIM-AR solution implementation and presents the different tasks needed for that. The second step is to consider reusing existing ontologies. Several classifications and taxonomies have been taken in consideration as ontologies in this research such as PVICAT (Amin, Mills, & Wilson, 2023) for the key functions, Human Computer Interaction (HCI) ontology (Costa et al., 2022) for the user and solution classes. The third step is to enumerate important terms in the ontology. In this step, terms are extracted to form a list of concepts (classes, relationships, and slots) from the data schema regardless of any overlap between the concepts they represent. The names of the selected terms have to follow a specific strategy as specified in define resources-naming strategy task. In this stage, all the classes and their related instances are identified. The fourth step is to define the classes and develop the class hierarchy. Several approaches can be used for developing a class hierarchy: namely, top-down, bottom-up and combination. Most of the ontologies are developed based on the top-down approach, which starts from an abstraction of a domain and continues to a concrete level. However, it has been argued that the bottom-up approach is more effective as domain modeling is based on raw and evidential data instead of theoretical conceptualization. In this research, the top-down approach is used for the reusable ontologies and concepts, while the bottom-up approach is selected for the development of the new ontologies. For example, the PVICAT was utilized to identify the classes of the key function classes. The researchers used that to develop instances for each class (Table 2). The instances were identified through the engagement of the researchers in two projects where BIM-AR are implemented. The fifth step is to define the properties of classes (slots); while the sixth step is to define the facets of the slots. The values of slots are described in different facets such as: value type, allowed values, cardinality, and other facet features. The value type facet can be described in different value types, such as string, number, Boolean and enumerated. The allowed value facets define the range of slot, and the cardinality facets define how many values the slot can have. In this research, the string value type is used for defining most of the slots for the classes' properties. Finally, the seventh step is to create the instance of classes in the hierarchy. The last three steps are ongoing part of this research. Several interviews and workshops will be conducted with end users to identify the instances especially for both the use case and requirement ontology.

The ARCHI ontology was initially modelled collaboratively using diagram.net, enabling researchers to visualize and connect classes and relationships. The resulting UML diagram was exported and converted to an OWL ontology using the Chowlk tool. This OWL file was then imported into Protégé for further refinement. Protégé provides a platform to construct domain models and knowledge-based systems by enabling the creation of classes, properties, and individuals. To develop a robust ontology of knowledge for the BIM-AR framework, certain design principles and best practices were followed. As highlighted by Hlomani and Stacey (2014), the ontology requires precise conceptualization of the domain knowledge through iterative refinement of definitions. Furthermore, Gruber's (1995) criteria of clarity, coherence, extendibility, minimal encoding bias, and minimal ontological commitment were adhered to ensure a well-founded ontology. By leveraging Protégé and adhering to established guidelines, the ARCHI ontology codifies the concepts and semantics required to represent the knowledge and relationships underlying the BIM-AR framework.

The ARCHI ontology consists of 5 key classes that characterize the problem space from different perspectives: Use Case, Requirements, Key Functions, Solutions, and Users (Figure 3). The Use Case class captures details about the context and goals of implementing AR into a BIM workflow. This includes the phase of integration such as design, construction planning, active construction, handover, or operations. It also covers specific applications and objectives, such as visualizing design models on-site, evaluating construction progress, or providing digital overlays for facility maintenance. Additionally, it describes the physical environment where AR will be utilized, for example a construction site or design office. The Requirements class contains the functional and non-functional needs that emerge based on parameters defined in the Use Case. For instance, a construction site application may require ruggedized hardware to withstand harsh conditions. Or an operations use case may require integration with existing facility management software platforms. Also, it covers the information requirements related to the information needed for the 3D models provided by the BIM systems. Based on each use case, we can define a Model View Definitions (MVD). Requirements provide a link between goals and necessary capabilities. The Key Functions class draws from the taxonomy of augmented reality capabilities synthesized by Amin et al (2023). It contains main categories of AR functionality. Each class also has associated instances as shown in Table 2. This provides a standardized vocabulary to describe AR features. The Solutions class characterizes the software, hardware, and other technological components of existing AR platforms. This includes parameters like software packages and versions, types of display hardware, interface modalities, tracking methods, input devices, and capabilities for data output or export. Lastly, the User class models the human users of the AR system. Both solution and user classes leverage existing ontologies related to human-computer interaction to fully define user-solution side factors. These 5 classes provide a structured foundation for evaluating and selecting optimal AR solutions. Use Cases define goals, Requirements outline needed capabilities, Key Functions provide a vocabulary of AR features, Solutions characterize technologies, and Users represent the human perspective. By mapping Use Cases to Requirements and Key Functions, then matching those to candidate Solutions while considering Users, the ontology enables principled assessment of how well a given AR platform suits a particular BIM use case need. This facilitates both targeted selection of existing tools and identification of areas requiring new solutions.

In summary, ontology-based modeling of the BIM-AR solution space can enable richer representations of end user perspectives, workflows, requirements, and project contexts. This knowledge base can then drive the circular participatory framework by connecting BIM-AR capabilities directly to construction practices and stakeholder needs. Additional research is underway on ARCHI's formal ontology development and its applications for guiding successful BIM-AR adoption.

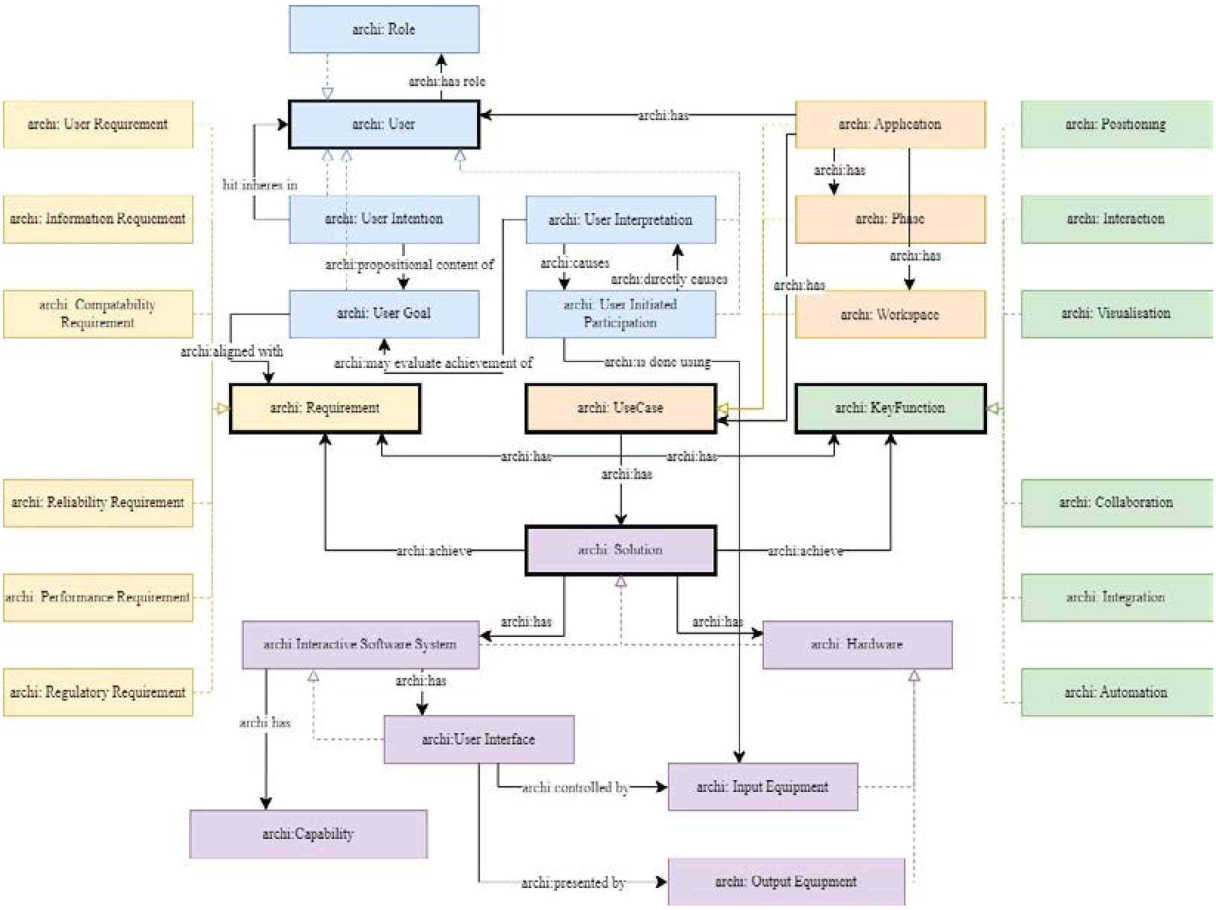

Figure 3: The main classes and relationships of ARCHI ontology.

Table 2: Key function classes and their instances and mapped solution capabilities

Key Function Class	Key Function Instances	Capabilities for the Key Function Instances
Positioning	Marker-based	Scan Marker
Positioning	Natural Feature-based	Scan Natural Feature
Positioning	Object-based	Scan Object
Positioning	Manual Mapping	Map Coordinates
Interaction	Modify	Move, Rotate, Resize, Delete
Interaction	Retrieve Information	Read, Download
Interaction	Store Information	Capture Image, Capture Video
Interaction	Add Information	Comment, Markup
Visualisation	Digital-Digital Inspection	Identify Clash, Identify Defect
Visualisation	Visibility Customization	Show, Change Color, Change Appearance
Collaboration	Issue communication	Upload Image, Upload Video, Stream
Automation	Visual Inspection	Class detection, defect detection
Automation	Report Generation	Progress report, clash report, defect report
Integration	Production and Programme control	Real-time integration with other systems
Integration	Presentation of external datasets	Real-time integration with weather and others
Integration	Improve/Extend existing function	API capabilities to extend functions

6. CONCLUSIONS

The BIM-AR Framework and ontology presented in this research offers a novel user-centric approach for designing and deploying augmented reality systems. Rather than taking a software-driven approach focused on tools like Unity, this framework emphasizes human-centered design with a focus on AR content. The core of this approach is a 5-step circular hybrid process that continuously evolves based on user needs and perspectives. To facilitate the sharing of information between process stages, the ARCHI ontology was developed to capture key data points and relationships. This human-focused approach represents a paradigm shift from traditional AR design methodologies. By putting the user at the center and iterating based on their requirements, the framework enables the development of more intuitive and purpose-driven AR applications. The ARCHI ontology also plays a key role by codifying knowledge to prevent information loss across the design lifecycle. Overall, the framework aims to create a more seamless AR experience by enhancing the symbiotic relationship between user and technology.

While initial expert review and case studies demonstrate the potential of this BIM-AR approach, further validation is required. Future work should concentrate on gathering additional use cases across different domains to refine the framework. More robust testing and evaluation of the ontology is also needed to ensure it adequately captures the necessary design knowledge. Extending the current ontologies with linked open data could also strengthen the knowledge-sharing capabilities. With further development and validation, this human-centric methodology could provide a new paradigm for AR system design that leads to more adopted and usable AR solutions.

This research presents a promising user-focused approach to AR design, moving away from software-centric methodologies. The BIM-AR Framework and ARCHI ontology provide an integrated solution to put human needs at the forefront. While more work is required, this pioneer research lays the foundations for next-generation AR systems that emphasize the human perspective over tools. With rigorous validation and evolution, this framework can enable AR developers to create more intuitive and purpose-driven applications that deliver value in various real-world contexts. The user-centric future envisioned by this research has the potential to transform augmented reality technology and cement its place as an integral part of how people interact with information and their environment.

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A REVIEW OF COMPUTER VISION-BASED PROGRESS MONITORING FOR EFFECTIVE DECISION MAKING

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ABSTRACT: *Construction Progress Monitoring (CPM) is a significant aspect of project management aimed to align planned design with the actual construction on site, the process ensures that the project is well within the control of the stakeholders involved and ensures the project is completed complying with the construction documents, on time, and within budget. Despite how central progress monitoring is to attaining project success and advances in technology, the progress monitoring is majorly implemented manually, which requires manual retrieving and processing of site data to compare with the planned design. This manual process is both time-consuming and prone to errors. Automating the task of progress monitoring involving real-time data acquisition and timely information retrieval can assist the project managers for effective decision making to the successful delivery of the project. Thus, the objective of this research was to assess the impact of computer vision (CV) – based progress monitoring as a driver for effective decision-making in project management. A qualitative methodology was implemented for this research using Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) to review and analyze studies on the application of computer vision (CV). The study reviews studies of CV based CPM process, highlighting its benefits against the traditional method of progress and the limitation to its adoption. Research findings from this paper provide an increased understanding and have a broader scope on the application of computer vision-based progress monitoring.*

KEYWORDS: Computer Vision, Construction progress monitoring, Decision-making, Project management

1. INTRODUCTION

Progress monitoring involves the processes required in tracking, evaluating and organizing the performance of a project, and identifying areas where modification needs to be implemented (PMOK, 2017). In the development phase of construction projects, site activities are tracked by the project manager using progress monitoring methods (Qureshi et al., 2022). Progress monitoring of a construction project is essential to the successful delivery of the project, this is because it entails recognizing the disparities between the planned design and the ongoing construction. As most tasks are interdependent, frequent inspections assist managers to detect anomalies early, avoid potential delays, and decide when to take remedial action (Reja et al., 2022). The progress monitoring phase is regarded as a complex task, it requires efficiency as it provides the essential inputs to the managers on site for prompt and informed decisions. This process, when done effectively helps to prevent cost and schedule overruns and improve the retrieval, management and processing of site data (Kopsida et al., 2015). According to Hanet et al. (2016), the limitations in manual and other conventional data acquisition procedures in progress monitoring cause more than 53% of construction projects to fall behind schedule and more than 66% of them to fall short financially.

The traditional method of progress monitoring of construction projects involves manual retrieving of data, information processing, documentation, and reporting on the project status. However, this method is time-consuming, information obtained are prone to human errors, and often report obsolete information which impedes effective decision-making from stakeholders (Rehman et al., 2022). To improve this, the process can be made effective through automation. Technologies exist for the automation of progress monitoring; with focus on retrieving data from the site, some of which include unmanned aerial vehicle (UAV), geographic information system (GIS), virtual reality (VR), augmented reality (AR), radio frequency identification (RFID), and global positioning systems (GPS). However, computer vision technology can be consolidated with these technologies to be implemented for progress monitoring. Computer vision (CV) is similar to the human vision, but utilizes machine learning algorithms or deep learning models in analyzing, predicting and making useful interpretation from data inputs which could be images or videos (Paneru & Jeelani, 2021).

For the automation of construction progress monitoring, a noticeable amount of research has been carried out. An overview study conducted by Ekanayake et al., (2021) on the application of computer vision-based interior construction progress monitoring. The study categorized the challenges that hinder the successful implementation of CV based interior construction project monitoring (CPM) into indoor objects, lighting condition and movements of the camera used. However, the study mostly focused on challenges for interior use. McCabe et al., (2017) also

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Roy Lan, Tulio Sulbaran, *A Review of Computer Vision-Based Progress Monitoring for Effective Decision Making,* pp. 856-864, DOI 10.36253/979-12-215-0289-3.85

investigated on indoor CV-based CPM, their study identified the challenges encountered using UAV's. for automated data retrieval. A related study by Kopsida et al., (2015) categorized the different stages involved in the automation process in terms of technology used and assessed, time efficiency, accuracy, cost and mobility. Most of the studies highlighted the need to overcome challenges for the successful implementation of a CV-based CPM. The objective of this study is to assess the impact of CV– based CPM as a driver for effective decision-making in project management. Investigating how this technology can improve decision making, by revealing its current level of adoption identifying the benefits, and the limitation involved to its application.

2. METHODOLOGY/APPROACH

For this study, a systematic review was conducted. This type of review involves identifying all relevant literature that is pertinent to the review question, critically evaluating identified literature and summarizing the findings (Gough et al,.2012). It helps to answer an important question or identify areas of importance relevant to the research question (Harris et al., 2014). The review begins by posing a research question, identifying relevant studies, critically evaluation of the studies, data collection, analyzing and structuring of the data, summarizing the evidence and reporting findings from the study (Khan et al., 2003). While the systematic review approach has been predominately used to conduct research in the medical field (Munn et al., 2018). It has been used several times in the field of construction management; for a review of sustainable construction management (Araújo et al., 2020), a review of the concept of buildability as it relates to construction management (Osuizugbo et al., 2022), and a review of the inter-relationship building information modeling (BIM) and safety in construction (Martínez-Aires et al., 2018). This is because the output from this type of review is usually comprehensive and exhaustive requiring an explicit methodology and helps present output in a structured sequence (Shamseer et al., 2015)

This systematic review was conducted using the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) which include four stages: Identification, Screening, Eligibility, and Includes (as shown in Figure 1). The databases sources used were Scopus, Web of Science (WOS) and Civil Engineering Database from the American Society of Civil Engineering (ASCE). Google Scholar was also used for the search of relevant studies. Keywords used in the databases for search include, "Computer vision" and "construction progress monitoring," as well as "Computer vision-based construction progress monitoring." For relevant extant literature, the search range was from the year 2005 upward. Duplicate files, and records having a different language from English that could not be translated were also excluded. Also, some papers had a methodological approach that did not align with the objective of this study, such papers were screened out. After screening and eligibility criteria the total number of papers evaluated and appraised for this study were 47.

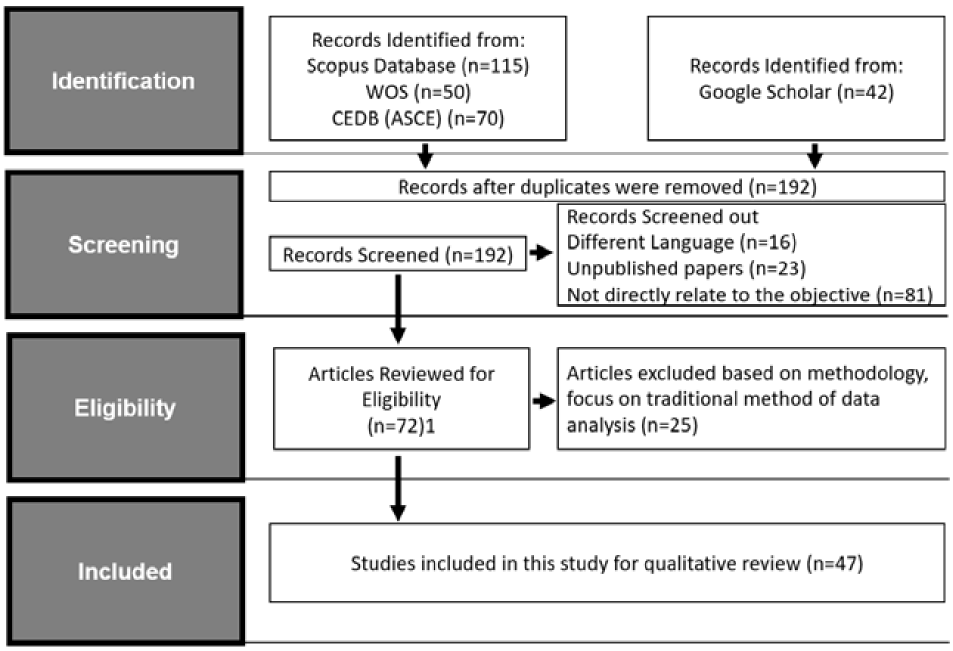

Fig. 1: Flowchart showing the systematic review process using PRISMA.

3. ANALYSIS AND RESULTS

3.1 Description of subprocesses of CV-based CPM process

In recent times, the application of CV-based CPM in project management has gained traction as the advantages it possesses has been observed to aid stakeholders for an effective decision-making process in the lifetime of a project (Braun et al., 2020). Different studies categorized the sub processes involved in CV-based CPM. The categories include, data acquisition, information retrieval, progress estimation, and output visualization (Kopsida & Vela, 2015; Rehman et al., 2022). Data acquisition and 3D reconstruction, as-planned & as-built modelling and progress monitoring (Reja et al., 2022). This review categorizes the process into three data acquisition, information retrieval and progress monitoring and visualization as shown in Figure 2. Each of the subprocess is summarized based on review of extant literature. The sequence is such that the data obtained automatically is analyzed to retrieve germane information such that there can be a systematic comparison between the as-planned and the as-built structure, and the disparities are made known in a comprehensible pattern. This section reviews the subprocesses associated with CV-based CPM.

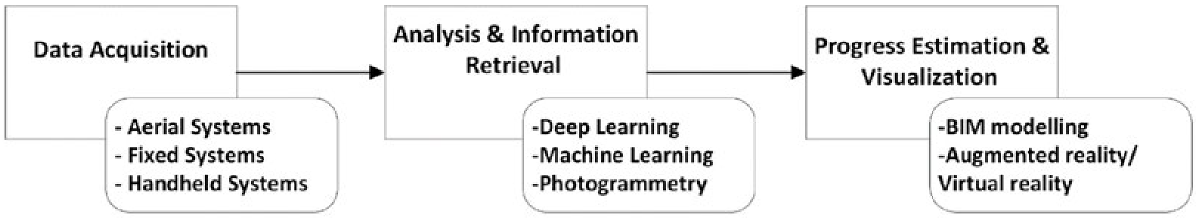

Fig. 2: Subprocesses of the CV based CPM.

3.2 Data Acquisition

Data format for automated progress monitoring include but not limited to two-dimensional (2D) or three-dimensional (3D) images, from cameras and depth cameras respectively (Omar & Nehdi, 2016). Videos obtained from videos cameras which could be fixed or mobile with the aid of technologies such as unmanned aerial vehicles (UAV), or unmanned ground vehicle (UGV). Also, a point cloud which involves tiny points which could be plotted for relevance in a 3D space or surface that can be sourced from 3D laser scanners like light detection and ranging (LIDAR) (Paneru & Jeelani, 2021a).

The construction site is known to be very dynamic in nature, consisting of various activities occurring most times intermittently (Ibrahim et al., 2009). Thus, the need to have a comprehensive overview that can be augmented by using digital images and videos in monitoring construction progress requiring little expertise because of the simplicity in its application. Table 1. Shows a summary of the data acquisition subprocess indicating the method of acquisition, devices utilized in this method, the benefits and the limitations to its use.

Table 1: Computer Vision Data Acquisition

Acquisition method	Devices	Benefits	Limits	Ref.
Aerial systems	UAV's integrated with sensors	- Provides a detailed coverage of site - Maneuvers complex areas which are difficult to manually navigate. - Can be integrated with sensors like cameras and laser scanners	- Requires expertise and certification to operate - It could be expensive depending on the specification - Precision when use is required	(D. Kim et al., 2019; McCabe et al., 2017)
Fixed Sytems	Surveillance cameras	- Provides stability for more clarity in data input obtained - Adequate for sustained period of data acquisition	- Restricted to one angle of view. - Not efficient for comprehensive coverage	(Benyeogor et al., 2020)

Handeld systems	Mobile cameras, tablets, smartphones	- Portable and handy making it comfortable for use - Provides flexibility in use, no restriction in getting elevations and angles - Best for use in getting up-close data for clarity	- Requires multiple takes to cover the entirety of construction space - Data obtained is subject to the users bias and accessibility.	(Jeon et al., 2006; Mahami, Nasirzadeh, Ahmadabadian, et al., 2019)

3.3 Information Retrieval & Analysis

The data retrieved in form of images and videos needs to be analyzed in order to obtain useful information, which will be vital for progress estimation (next sub-process). Some of the commonly used methods includes traditional machine learning technique which includes support vector machines, Hough transform, artificial neural network and deep learning techniques using deep convolution neural networks (CNN). Zhu et al., (2010) proposed a novel technique using Hough Transform Technique to analyze 373 images of large-scale concrete columns for inspection of surfaces to detect defects, the technique when evaluated performed well with a high precision of 89.7% and recall of 84.3%. Kim et al., (2013) presented a method for measuring construction progress based on information included in 4D building information modelling (BIM) and 3D data, the data was classified using support vector machines (SVM) classifier, the SVM model was trained using a labelled 3D data. Because the initial as-built statuses of some components may be inaccurate as a result of an incomplete 3D data set, a two-stage revision was performed. The first stage was based on the sequence of activity execution and the second stage was based on the connectivity between components. Both the sequence of activity execution and the connectivity between components were stored in the BIM. The final as-built statuses produced by this process may be used to determine actual finish dates and to measure actual construction progress. The accuracy of the proposed method was validated using an incomplete set of 3D data acquired on an actual construction site achieving 99% precision rate on the second revision. Additionally, Wang et al., (2021) proposed a vision-based framework for monitoring precast walls during construction, using convolution neural networks (CNN) based computer vision method including Mask R-CNN and DeepSORT to realize object detection, instance segmentation and multiple objects tracking on the dataset obtained from surveillance cameras. The output from the study confirmed the detection rates of CNNs are fast compared to other techniques, this agrees with studies from (Paneru & Jeelani, 2021b; Sultana et al., 2018). Other relevant analytical methods include, Simultaneous Localization and Mapping (SLAM) (Kim et al., 2018), Structure From Motion (SFM) (Mahami et al., 2019),) Histogram Oriented Gradients (HOG) (Memarzadeh et al., 2012 ,and Laplacian of Gaussian (LoG) (Hui & Brilakis, 2013). Table 2. Shows a summary of the information retrieval and analysis subprocess indicating the analytical method, models utilized in the method, the benefits and the limitations to its use.

Table 2: Information Retrieval & Analysis.

Analytical method	Model	Benefits	Limitations	Ref
Traditional Machine Learning	HOG, LoG, SURF, Hough transform, SVM	- Can handle large data - Reliable and high accuracy when trained with balanced dataset.	- Requires large dataset - Requires preprocessing and feature extraction of data	(Zhu et al., 2010)
Deep learning	Mask R-CNN, DeepSORT	- Models can learn patterns from data in high speed - Models trained usually have accuracy - Requires no manual feature extraction or engineering	- Requires high end hardware for processing. - Requires large dataset fir better analysis,	(Z. Wang et al., 2021)
Photogrammetry	SFM, SLAM	- Usually cost effective in comparison with laser scanners - Flexibility of use on construction sites	- Long processing time - Requires hardware with	(Kim et al., 2018)

3.4 Progress Estimation & Visualization

This subprocess makes use of the information retrieved by analyzing the information retrieved. This process is usually a comparison between the as-planned model and the as-built model. The comparison is also known as registration as identified from various literature (Kopsida & Vela, 2015; Rehman et al., 2022). The output is significant for project controls as it gives an update on the project schedule; if the project is on schedule or behind schedule by showing the extent of construction which has been put in place on site (Reja et al., 2022). The result of this comparison is necessary in identifying the successive steps which the stakeholders can take in order to meet the project's objective. The concept of building information modelling (BIM) is very prominent in this subprocess, as the format of the as-planned model can be presented in the four-dimensions 4D BIM model for comparison. After the comparison process, a matching process to see the disparity between the observed and the planned is conducted. The use of voxels, object matching, and probabilistic model have been used to detect progress. This progress is visualized using technologies which enable immersion such as Augmented reality and virtual reality (Ahmed, 2019). Several studies have identified the use of AR and VR as better visualization tools for progress monitoring (Omar & Nehdi, 2016; Rohani et al., 2014). In a case study, Meža et al., (2015) conducted a survey comparing AR with traditional visualization techniques like Gantt charts, AR ranked highest in "understandability of project documentation in monitoring of construction" and "usability of project documentation in monitoring of construction". Wang et al., (2013) proposed a framework for integrating BIM with AR; the platform which is able to couple BIM and AR so that information about 'as-built and as-planned progress' as well as 'current and future progress' can be obtained and presented visually. Comprehensively, consolidated studies have identified AR and VR technologies to be ideal visualization techniques in progress monitoring, as they have shown to facilitate understanding of construction progress estimation.

3.5 Cost and Time-factor of Traditional and Computer Vision-based Progress Monitoring

In project management, cost and time are very significant factors that are used in defining the success of the project, and mangers are constantly seeking ways to optimize cost, be on schedule and to meet standard requirements of a construction project (Chan et al., 2004; Luong et al., 2021). They are also very important criteria which managers and stakeholders consider during decision-making in construction. Hence, it is imperative to include these parameters for the comparison of CV-based CPM and traditional progress monitoring. The cost of setting up a CV based CPM is relative depending on the devices used in each subprocess. In comparison to the traditional method which requires no automation or negligible technology, is perceived as an expensive process. Expenses including purchase of equipment, software, maintenance cost, technical support personnel and the training of users (Omar & Nehdi, 2016). Additionally, numerous researches have shown that CV based CPM is a time-saving and efficient process (Golparvar-Fard et al., 2009; C. Kim et al., 2013). In a case study conducted by Braun et al., (2020), using deep learning technique with sfm-based data consisting of categorized images of formwork, scaffolding and columns, a real time comparison between the as-planned and as-built, to detect progress of site activities was achieved in real time. When evaluated, the method produced a high precision of 90% in detection rate, enormously saving time in the process.

3.6 Comparison between Traditional progress monitoring and CV based CPM

In this section, the CV-based CPM was compared with the traditional progress monitoring using relevant indices which can assist stakeholders when making decision on both methods. Table 4 shows summary was obtained from the systematic review of literature on the application of both methods.

Table 4. Summary of the comparison between CV-based CPM and Traditional progress monitoring

Evaluation Criteria	CV-based CPM	Traditional Progress Monitoring
Data Acquisition	Reliable and timely	Depends on the sense of judgement of the personnel executing the task
Information retrieval & Analysis	Requires expertise from the personnel performing the analysis, mistakes can be spotted and quickly	Requires more of human input, personnel involved in the process needs to be properly trained to avoid errors, which will lead to impact on the project.
Progress monitoring & visualization	The use of BIM/virtual reality/augmented reality gives a sense of realism and immersive and provides sturdy detail of the project.	Doesn't provide the realism and immersion that CV based CPM provides. Output might be difficult to interpret.
Cost	Process can be expensive, especially cost of hardware, software and training	Cost relatively cheaper when compared to CV based CPM

Time	Generally, saves time, notable for efficiency in site management.	Time consuming process

3.7 Limitations to the application of CV-based CPM

Despite the benefits which CV based CPM process offers to stakeholders to enable effective decision making, there still exist some barriers which leads to the hesitation to its adoption. Some of these limitation include; lack of technical expertise on software and hardware, adverse weather conditions, occlusions, specifications of data acquisition device. These limitations were grouped into three which include, environmental factors, technical factors and human factors.

Environmental factors are the barriers within the site location which prevent successful application of CV-based CPM. This includes, the impact of weather, for automating the data acquisition subprocess. The impact of the weather isn't negligible as adverse weather condition distorts the quality of the image which inadvertently leads to poor analysis of the input (Omar & Nehdi, 2016). Poor lightning condition is also significant in the processing of input data. Hamledari et al., (2017) proposed a framework that automatically detects components of an interior partitions using 2D images, their study inferred on the significance and impact of good lightning in order to achieve good results on the detection of site objects. Other environmental factors include, air quality, site condition, due to varying activities, certain sites may be too clustered leading to data acquisition device hindered view of the entirety of work site space.

Technical factors include the factors related to the technology implemented in each of the subprocess. Some are, the specification of data acquisition devices, image and video capturing devices, knowledge on the appropriate devices for the type of data required. Also, for the information retrieval, knowing the proper analysis on the data can be challenging, certain techniques require a lot of data to be trained in order to give a desired output (Moragane et al., 2022). Aerial systems like the UAVs require certifications, and a level of technical knowledge to operate, this can be challenging especially if it's a small-scale project involved.

Human factors are largely critical to the successful implementation of CV-based CPM. Barriers such as privacy issues, and reduced creativity from workers due to the displeasure caused by the feeling of being monitored (Ibrahim et al., 2009; Moragane et al., 2022). Despite this method being an automated process, certain subprocesses require the input of personnel in order to operate. For example, at the information retrieval subprocess, the technical know-how of the personnel executing the task is significant and as such requires requisite training (Paneru & Jeelani, 2021a).

3.8 Intellectual Merit / Broader Impact

The intellectual merit of this work is how it reviews CV based CPM, highlighting on the process involved, developing an evaluation criterion to compare CV-based CPM with the traditional monitoring process, also identifying limitation to its application in project management. The broad impact of this work is will yield an increase understanding of CV based CPM by as an alternative to the traditional monitoring process, as its current level of adoption is still at its nascent stage. A simple holistic understanding of the process by stakeholders can assist in a more informed decision towards project monitoring in project management.

3.9 Conclusion

In project management, construction progress monitoring is a very significant process in achieving a successful project delivery. However, most projects still undergo the traditional manual progress monitoring process. The process has been identified to be time consuming, error prone and subject to the bias and technical know-how of the personnel involved in the process, and this concern leads to the need to automate the process. The objective of the paper was to assess the impact of CV based CPM as an effective decision making tool by highlighting key subprocesses involved in the process, including listing an evaluation criteria for comparing the CV based CPM with the traditional manual monitoring process, and to identify barriers to its adoption as a project monitoring tool in project management. A systematic review was conducted, to evaluate literature relating to the topic. Databases from Scopus, WOS, ASCE and Google scholar were sources of data for the review, PRISMA analysis was used in screening all the papers in order to ascertain relevant literature for this study.

The outcome of this study gave a concise description of subprocesses associated with CV based CPM process. Images and videos are currently the most utilized data in this process and this is most common because of its ease of accessibility and availability of processing systems. Aerial systems which include the use of drones and augmented reality googles show great potential as an effective data acquisition device. Deep learning technique using CNN due to its speed in detection can be integrated with aerial systems for an effective monitoring system with real time output. Lastly, the study highlighted limitations for the applications of CV based CPM and categorized these as human environmental and technical factors, and the review identified technical factors to be a significant factor among others. In short, this study is important because it provides a simple holistic understanding of the process thus aiding stakeholders with accurate knowledge for decision-making towards CV based CPM in construction project management.

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SEMI-AUTOMATED VISUAL QUALITY CONTROL INSPECTION DURING CONSTRUCTION OR RENOVATION OF RAILWAYS USING DEEP LEARNING TECHNIQUES AND AUGMENTED REALITY VISUALIZATION

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ABSTRACT: *The construction industry stands to greatly benefit from the technological advancements in deep learning and computer vision, which can automate time-consuming tasks such as quality control. In this paper, we introduce a framework that incorporates two advanced tools - the Visual Quality Control (VQC) tool and the Digital Twin visualization with Augmented Reality (DigiTAR) tool - to perform semi-automated visual quality control in the construction site during the execution phase of the project. The VQC tool is a backend service that detects potential defects on images captured on-site using the Mask R-CNN algorithm trained on annotated images of concrete and railway defects. The surveyor, aided by the Augmented Reality (AR) technology through the DigiTAR tool, can in-situ confirm/reject the detected defects and propose remedial actions. All the quality control results are recorded in the relevant BIM model and can be viewed on-site overlaid on the physical construction elements. This solution offers a semi-automated visual inspection that can speed up and simplify the quality control process, especially in case of large linear infrastructures, illustrating the added value of AR-based applications in Digital Twins.*

KEYWORDS: *BIM, Augmented Reality, AR in Construction, Deep Learning, Computer Vision, Visual Inspection, Digital Twins*

1. INTRODUCTION

A prominent challenge in the construction industry is the ability to swiftly and seamlessly adapt to changes. To address this issue, an effective approach involves harnessing the power of computer-aided tools that can replace time-consuming activities. By integrating such tools into construction processes, valuable time and effort are saved, leading to significant cost reductions. By introducing digitalized processes to handle repetitive and labor-intensive tasks, construction projects can enhance their adaptability and responsiveness to changes. This allows teams to allocate their resources more efficiently, enabling them to focus on more critical aspects of the project. Furthermore, the digitalization of manual processes and the use of machine learning algorithms facilitate faster decision-making and reduce the likelihood of errors, as they can process vast amounts of data accurately and consistently. The increased accuracy and efficiency provided by these tools contribute to improved project outcomes and overall productivity.

This study introduces a semi-automated approach for visual quality control during the execution phase of construction projects. The proposed framework leverages recent technological advancements in deep learning and computer vision. It is designed to incorporate two essential components: the Visual Quality Control (VQC) tool and the Digital Twin visualization with Augmented Reality (DigiTAR) tool. The VQC tool serves as a backend service; it incorporates a deep learning network trained to detect concrete and railway defects in construction site images. The DigiTAR tool harnesses the power of AR technology to provide a unique visualization experience of the BIM model. Through DigiTAR, users can immerse themselves in the construction site and witness the 3D Building Information Modeling (BIM) model in real-time, where the digital BIM model components are overlaid onto the physical components. DigiTAR is responsible for visualizing the VQC results on-site. This means that key stakeholders, such as the project manager and quality manager of the construction project, can conveniently review and confirm these results firsthand. Their confirmation of these VQC results is pivotal, as it determines whether additional remedial works are assigned to the components identified in the VQC data. By having access to such crucial data on-site, decision-making processes can be expedited, and effective collaboration among stakeholders is further enhanced.

The novelty of the proposed approach in comparison to other existing solutions is that it simultaneously allows: (1) a collaborative inspection of construction sites (different inspectors, both in-situ and asynchronously); (2) different types of annotations (texts, strokes, images, 3D models); (3) geolocated annotations (related to specific

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Apostolia Gounaridou, Evangelia Pantraki, Vasileios Dimitriadis, Athanasios Tsakiris, Dimosthenis Ioannidis, Dimitrios Tzovaras, *Semi-Automated Visual Quality Control Inspection During Construction or Renovation of Railways Using Deep Learning Techniques and Augmented Reality Visualization,* pp. 865-876, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.86

elements of the virtual BIM model); (4) the monitoring and editing of registered annotations; and (5) the in-situ visualization of both the designed and the actual state of the building by means of the AR technology. By incorporating these novel features, the proposed approach significantly improves the inspection process, fosters collaboration among stakeholders, and ensures higher-quality construction outcomes. This comprehensive and innovative approach addresses critical challenges faced in the construction industry, promoting efficiency and excellence throughout the project lifecycle.

The rest of the paper is structured as follows. In Section 2, related work is surveyed, focusing on: i) visual inspection methods of railways using deep learning techniques and ii) AR approaches for on-site construction inspection. In Section 3 we present the bundle of the quality control tools in detail, addressing its design and technological and implementation issues. Section 4 provides the results of the evaluation process and a case study demonstration example of utilizing the proposed framework in a real environment. Finally, the conclusion section summarizes the main findings.

2. RELATED WORK

In this section, the relevant literature review is presented. Firstly, we focus on the automated inspection of construction sites using mainly deep learning techniques. Secondly, research approaches concerning the construction sites inspection with the use of AR technology are briefly presented.

2.1 Visual inspection using deep learning techniques

In recent years, deep-learning algorithms have shown remarkable performance in image object recognition and Convolutional Neural Networks (CNNs) have attracted wide attention as an effective recognition method. CNNs have been applied successfully to detect structural damages. Many studies have been conducted focusing on binary classification issues, such as crack detection (Brien et al., 2023), including additional estimations regarding the depth of the crack (Laxman et al., 2023) or the width of the crack (Meng et al., 2023). In addition, multiple surveys have been focused on crack detection and segmentation (Attard et al., 2019; X. Xu et al., 2022), corrosion detection (Atha & Jahanshahi, 2018; Papamarkou et al., 2021), bughole detection (F. Wei et al., 2019), and multi-damage detection (Cha et al., 2018; Kumar et al., 2021).

Focusing on railways inspection, most of the studies examine the defects on the railway track lines due to the long-term pressure from train operations and direct exposure to the natural environment, which have a direct impact on the safety of train operations (Cao et al., 2020; Guo et al., 2021; Liang et al., 2019; Zhang, Liang, et al., 2021). In (Gan et al., 2017), an automatic inspection system for rail surface discrete defects due to fatigue was created and tested, extending the literature review with the Rail Surface Discrete Defects (RSDD) dataset. The Rail-5k dataset (Zhang, Yu, et al., 2021) includes the thirteen most common types of rail defects and is considered a benchmark dataset for rail surface and fastener defects. In (Zheng et al., 2021), a multi object detection method based on deep CNN is proposed, achieving a non-destructive detection of rail surface and fastener defects. In this method, rails and fasteners on the railway track images are firstly localized by YOLOv5. Then, surface defects of the rail are detected and segmented based on Mask R-CNN (He et al., 2017), while a ResNet framework is used to classify the state of the fasteners. In (X. Wei et al., 2019), the authors compare different methods for fastener defect detection and recognition, concluding that with the Faster R-CNN the fastener positioning and recognition can be carried out simultaneously. (Y. Xu et al., 2021) proposed a novel method for tunnel defect inspection (such as leakage and spalling) based on the Mask R-CNN. The network was modified appropriately (extra feature pyramid network and edge detection branch) to achieve a higher accuracy in tunnel defect detection and segmentation. (Xue & Li, 2018) proposed a fully convolutional network (FCN) model for automatic classification and detection of tunnel lining defects (such as leakage, crack, and segment joint). The authors compare their proposed method with traditional convolutional networks (such as VGG) and Faster R-CNN, concluding that the proposed model is very fast and efficient. In (Xue et al., 2020), a deep learning-based model for automatic calculation of the water leakage areas of a shield tunnel surface is proposed. Optimization measurements, such as data augmentation, transfer learning, and cascade strategy, were adopted to improve the performance of the original model.

In conclusion, many of the existing studies focus on concrete surfaces and tackle the issue of binary classification (e.g., crack/non-crack). To the best of our knowledge, studies that concern multiclass classification and detection focus mostly on long-term concrete defects. In addition, they mainly refer to bridge or rail track deterioration and defect detection.

2.2 AR for construction inspection

In (García-Pereira et al., 2020) an AR-based tool is developed for the inspection of prefabricated buildings. The tool has been evaluated positively, as it allows collaborative inspection, supports multi-type, geolocated annotations, and in-situ augmented reality visualizations. (Chi et al., 2022) present a method, which combines AR and laser-scanning technologies to provide intuitive and accurate rebar inspection. The as-built (point clouds) and as-planned data are compared to provide discrepancy information for the inspectors. With the AR, the user is able to visualize the rebar inspection outputs and provide rework instructions. (Zhou et al., 2017) propose an AR-based method to rapidly inspect segment displacement during tunneling construction. The quality inspector is able to overlay the baseline model, which is established according to the quality standard, onto the real structure and measure the differences between them. In (Kwon et al., 2014), a defect management system for reinforced concrete work is presented, utilizing BIM, image-matching, and AR. The authors developed two separate applications: an image-matching system for quality inspection without visiting the construction site (by comparing the 2D images from the BIM model with the real on-site images) and a mobile AR application for workers and managers to detect dimension errors/omissions on-site, in order to save time and reduce rework costs.

The proposed framework combines the automated image-based visual inspection, powered by advanced deep learning techniques, with AR on-site visualization and confirmation of the QC outputs. The scope is to provide an efficient solution that not only saves time, but also prevents chained construction error and reduces the need for costly reworks during the construction phase.

3. MATERIALS AND METHODS

The work presented in this paper is developed as part of the COnstruction phase diGItal Twin mOdel (COGITO) project (*COGITO Project*, n.d.). The COGITO project offers, among others, a bundle of tools for conducting a semi-automated visual quality control during the construction phase of large linear infrastructures (especially railways) aiming at minimizing the effort and the time usually needed for on-site visual inspection.

Within COGITO, an image-based inspection system is developed, complemented with AR visualization and interaction. Firstly, as-built data (2D images) are acquired on-site using various capturing devices, such as smartphones, cameras, and AR devices. Secondly, the acquired images are processed (e.g., cropping, resizing) by a dedicated Visual Data Pre-processing tool. At this point, each processed image is linked to a specific QC task and to the respective BIM elements depicted in the image. In the third step, the data are forwarded for the automated visual quality control. Since each image is linked to a specific element of the BIM model, the quality control results and the detected defects are also linked to elements of the BIM model (fourth step). Therefore, the inspector is able to visualize and confirm the QC results on-site using AR with each QC result pinned on the corresponding BIM element (fifth step). The inspector can either confirm or reject each detected defect and propose a rework or a mitigation work, if needed (sixth step). Finally, workers perform the proposed remedial works (seventh step). Since the defects, as well as the proposed reworks, are recorded to the BIM model, the defect management is facilitated, resulting in cost and time savings during the construction phase. The overview of the COGITO Visual QC framework is presented in Figure 1.

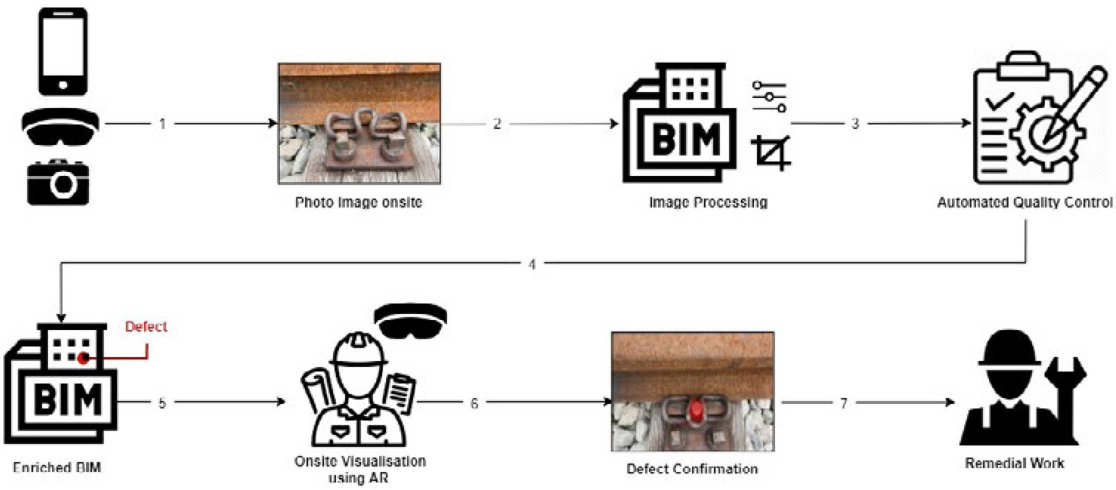

Figure 1: COGITO QC workflow

3.1 On-site Data Acquisition

Since it is necessary to capture images or videos of specific new as-built elements, various means of data acquisition can be utilized, such as cameras, mobile phones, drones and/or AR glasses (*Microsoft HoloLens2*, n.d.). Regardless of the means used for this purpose, some generic guidelines should be followed during this procedure, in order to achieve successful automated quality control and optimize the quality of the obtained results. More specifically, the images should be approximately 1000 x 1000 pixels, without spray markers or other signs that may affect negatively the QC results. They also need to be close shot and clear (not too generic or blurry) and the lighting conditions should be appropriate to ensure that the desired element is visible in the image. In case of video, the captured video will be automatically converted into a panorama image during the data processing phase. However, the video duration should be approximately five seconds (less than eight seconds) in order to generate an appropriate panorama image. In addition, a straightforward path should be followed while capturing. It is recommended to avoid rotating, shifting, sliding back or maneuvering. Finally, all the conditions for image capturing (close shot and clear, sufficient lighting conditions, without spray markers) should be also applied in case of video capturing.

3.2 Visual Data Pre-processing

After the on-site data capturing, the images need to be prepared and uploaded for the automated quality control. Within the COGITO project, this can be achieved both via a Pre-Processing Desktop application or the DigiTAR application in-situ, if the images are captured with a mobile phone or with HoloLens 2, respectively. The images should be linked to a specific QC task and BIM element before processing. The image processing includes filter application, such as modifying the contrast or the brightness of the photo and resizing or cropping it to focus on the region of interest. The aim of preprocessing is to prepare the image for the automated quality control. In case of uploading a video, a respective panorama image is generated automatically and the user is able to process it in a similar way to the normal images. Once all the desired data (images and videos) have been processed and related to a QC task, they are forwarded for the automated quality control. In Figure 2, the COGITO visual data pre-processing workflow is depicted.

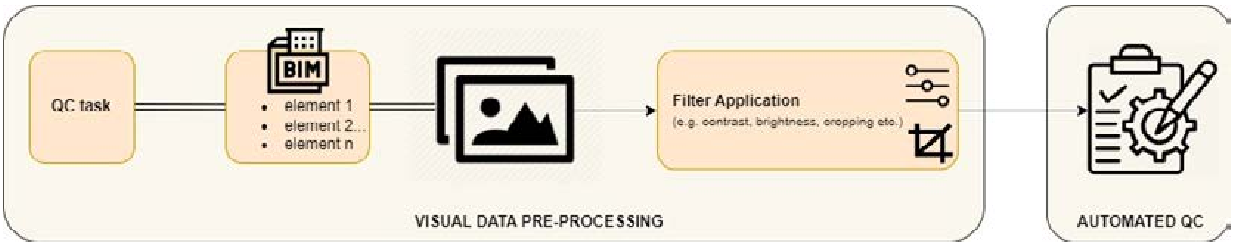

Figure 2: COGITO Visual Data Pre-Processing workflow

3.3 Automated Quality Control

The preprocessed visual data are forwarded for the automated quality control. Since the scope of the COGITO solution is to perform an automated quality control during the construction phase of new large linear infrastructures (especially railways), the VQC tool has been specifically designed to serve this purpose and the chosen defect classes for the algorithms are tailored to address construction-related issues, rather than covering defects attributed to aging of materials. Based on the deep learning algorithms employed, the VQC tool is able to detect defects, which are likely to occur during the railway construction, on concrete and steel elements. More specifically, in case of concrete surfaces, the system is able to detect cracks or honeycomb defects, while in case of railway steel elements, it detects missing clamps, missing screws, and missing screw nuts. The defect detection includes both the object detection and semantic segmentation. The goal of object detection is to classify individual defects and localize them using a bounding box and the goal of semantic segmentation is to distinguish the defects at the pixel level.

3.3.1 Dataset Preparation

For the concrete case, a dataset with concrete cracks and honeycomb images was built. The images have been combined from (*Crack Segmentation Dataset*, n.d.) and (*Concrete Crack Segmentation Dataset*, n.d.). Furthermore, additional data (with high resolution and image size) captured by Unmanned Aerial Vehicles (UAVs) were used. The original large UAVs images were divided into several smaller images using a Python script. For the steel case, a dataset was built using images collected from an above ground railway construction site in Munich. The images depict three types of defects that can occur during the railway placement: missing clamp, missing screw, and missing screw nut. The data were resized to be consistent and have fixed dimensions (i.e., 1024 x 1024 pixels). Since the scope of the project is the automated quality control in railways, underground areas are likely to exist. Therefore, an offline data augmentation was performed to the images, in order to reduce the brightness and simulate the tunnel lighting conditions. For the concrete dataset, 1970 images were used in total to train the model for detecting the two aforementioned types of concrete defects. The ratio of the training and validation sets was almost 4:1; the training and validation sets comprise 1544 and 426 images, respectively. For the steel dataset, 2195 images were used in total to train the model for detecting the railway joint defects. The ratio of the training and validation sets was almost 5:1; the training and validation sets comprise 1720 and 493 images, respectively. The annotation of the dataset is an important and fundamental step. The image label tool LabelMe (Russell et al., 2008) was used to label the masks of the objects in both cases (concrete and steel elements).

3.3.2 Transfer Learning Implementation

The VQC tool is designed to detect defects on concrete surfaces and in steel railway elements. For this purpose, two different models (for concrete and steel case, respectively) have been trained using the Matterport's implementation of Mask R-CNN for TensorFlow2.0 (Abdulla, 2017). Mask R-CNN is an extension to the original Faster R-CNN, by adding a branch for predicting segmentation masks on each Region of Interest (RoI) using an FCN, in parallel with the existing branch for classification and bounding box regression (He et al., 2017). Therefore, Mask R-CNN not only outputs a class label and a bounding box, but also a binary mask for each detected object. The network was trained with a learning rate of 0.001, momentum of 0.90, and weight decay of 0.0001. ResNet50 was used as a backbone architecture. The IMG_SIZE and the TRAIN_ROIS_PER_IMAGE parameters were set to 512 and to 80, respectively. The RPN_ANCHOR_SCALES parameter was set to (16, 32, 64, 128, 256). The value of MAX_GT_INSTANCES and DETECTION_MAX_INSTANCES parameters were set in both cases to 5. Since a transfer learning technique was applied, the COCO dataset was used to pre-train the network and initialize its weights. Finally, only the head layers were re-trained and fine-tuned on the appropriate datasets.

The configuration of system environment was Python 3.8, Keras 2.4.3, TensorFlow 2.4.1, CUDA 11.0, and CUDNN 8.0.5 on a computer with a NVIDIA GeForce RTX 3080 GPU and a Core i7-10700 @2.9GHz CPU, with 32 GB RAM memory.

3.4 AR Visualization

The QC results obtained by the automatic visual quality control are visualized on-site with the DigiTAR tool, in order to be confirmed by the relevant stakeholders, such as the project manager and the quality manager of the construction project. Based on their decision, additional remedial works can be assigned to the components included in the VQC results. In addition, the DigiTAR tool enables the AR visualization of the BIM models. The user is able to view the 3D BIM model on-site, i.e., view the 3D BIM elements overlaying the physical elements. The workflow of the QC results confirmation process within DigiTAR is depicted in Figure 3. DigiTAR is developed using the Unity 3D Game Engine and is specifically optimized to operate on (*Microsoft HoloLens2*, n.d.) devices. In Section 3.4.1, the BIM model visualization functionality of the DigiTAR tool is described in detail, while the registration process of the BIM model is described in Section 3.4.2. Details for the visualization of the relevant QC results and the data acquisition functionality of DigiTAR are enclosed in Sections 3.4.3 and 3.4.4, respectively.

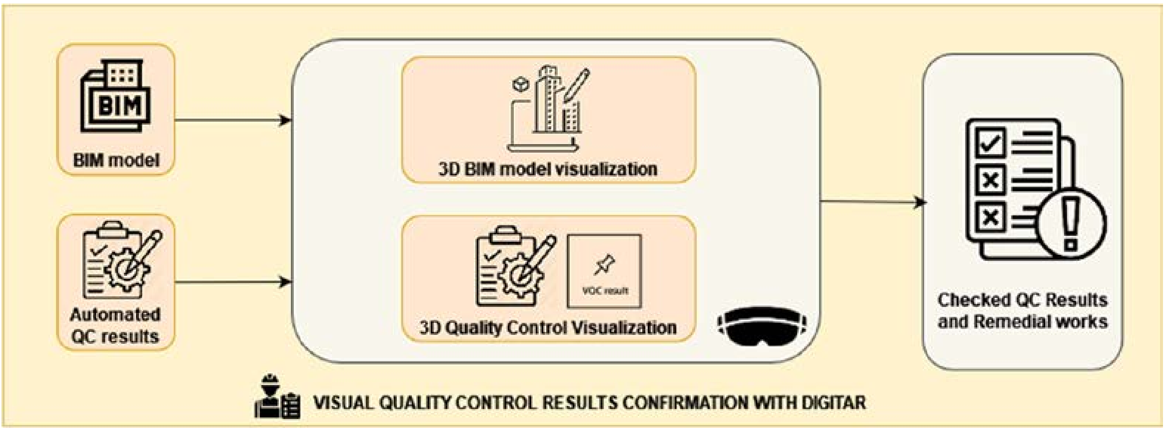

Figure 3: DigiTAR BIM model visualization and QC results confirmation workflow

3.4.1 BIM model visualization

BIM model visualization is a key functionality of the DigiTAR tool. To enable this functionality, DigiTAR requires as input the BIM model of the construction site in an Industry Foundation Classes (IFC) format. Additionally, the tool needs the 3D geometry representation of the BIM model. The geometry representation of the BIM model is achieved through the transformation of the IFC file to a file format supported by the Unity Game Engine, such as the OBJ file format.

The IFC parsing process in DigiTAR involves importing the IFC and OBJ files, extracting the IFC data, and mapping those data to the 3D model. This process is handled by custom C# classes based on the Xbim library (Lockley et al., 2017). The IFC parsing process is implemented by recursively querying and retrieving data from the IFC file for the elements of the IFC file using the IFC Schema. A GameObject is generated for each IFC element and parent/child relationships are established based on the hierarchical relationships of the elements in the IFC file. Upon completion of the IFC parsing, the result is a hierarchical structure, where each GameObject has its own IFC properties extracted in a dedicated C# class.

3.4.2 BIM model registration

After visualizing the BIM model, the next crucial step in the DigiTAR tool is registration, which involves aligning the 3D model of the construction site to the actual site. Within DigiTAR, registration relies on image targets using the Vuforia SDK (*Vuforia Engine*, n.d.). An image target is an image that the application running on HoloLens will detect and track. This image will be the link between the static 3D world (BIM model) and the real world.

The image target is printed and positioned at a location in the real world, ensuring that it is accessible to the person wearing the HoloLens. At the same time, an identical image is placed in exactly the same spot in the 3D BIM model. To enable the detection of the image target, the user uses speech command "Scan for marker". This way, the data captured by the HoloLens sensors and cameras are utilized by DigiTAR for image target detection. More specifically, features are extracted from the HoloLens camera stream and are compared to the reference features already extracted from the image target. In the context of pattern recognition, the features that are extracted in advance from the image target constitute the pattern that the algorithm searches across the continuous flow of data streams. When the person wearing the HoloLens looks at the image target, the features extracted from the data stream of HoloLens are matched to the pattern of features belonging to the image target. Therefore, the image target is detected and registration is performed.

After successful registration of the 3D BIM model and in order to maintain it, the registered 3D BIM model is continuously tracked. In the DigiTAR application, the registration of the 3D BIM model is tracked using spatial anchors; spatial anchors represent important points in the world that the HoloLens coordinate system keeps track of over time. The registered 3D BIM model can be set as a spatial anchor using the dedicated in DigiTAR speech command "Anchor model". This way, the next time the user opens the DigiTAR application, the 3D BIM model is loaded aligned to the real world without the need to repeat the registration process.

3.4.3 QC results visualization

The QC results are visualized using 3D QC tags that are pinned on the elements of the BIM model that are included in the QC result. The QC tags are displayed in Figure 4. To visually notify the user, the color of the tag is indicative of the relevant QC results: green if no defect has been detected, red if all QC results have detected defects, and orange if the QC results include both detected defects and no defects.

Figure 4: Visual Quality Control tags are pinned on the involved elements

Firstly, the QC tag is placed on the center of the element's bound. When an element with a QC gets in the user's field of view, the QC tag dynamically changes its position and rotation while staying on the surface of the 3D element. More specifically, the position of the QC tag is dynamically adjusted to the user's height, while the rotation of the QC tag is dynamically adjusted so that the QC tag is displayed vertically in front of the user. A view of a 3D BIM model with pinned QC tags is depicted in Figure 5. Moreover, if the user selects (using the Hand ray gesture on HoloLens[1]) a 3D element that has a pinned QC tag, the QC tag follows the movement of the user's hand, while staying on the surface of the 3D element. An illustration of this feature is depicted in Figure 6. If the user performs the air tap gesture[2] on a QC tag, the related VQC results are displayed using dedicated AR menus, as described subsequently in Section 4.2.

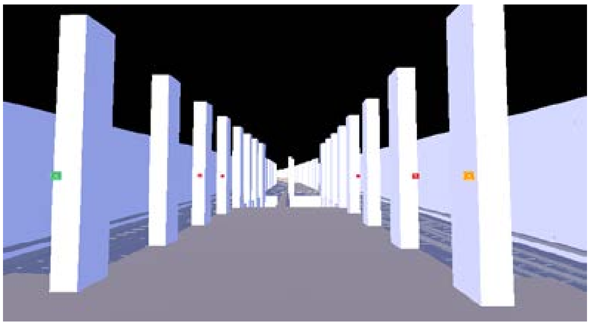

Figure 5: View of the 3D BIM model with QC tags

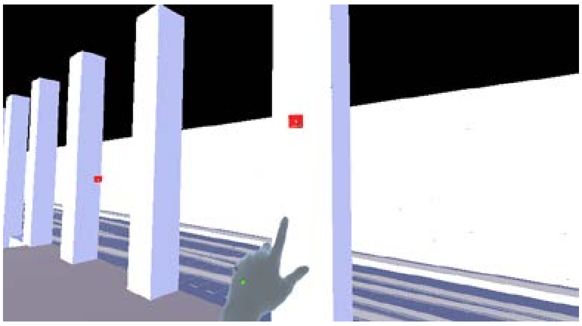

Figure 6: When selected, the QC tag follows the movement of the user's hand

3.4.4 Data acquisition and pre-processing

DigiTAR acts as a data acquisition tool for gathering images on-site to be used for automated quality control. This functionality is implemented in DigiTAR using a hand-attached menu[3]. When the user selects the dedicated "Capture Image" button, an asynchronous process is initiated to assess the HoloLens camera stream for photo capturing.

When the user looks at what they want to capture and say "Capture image", a photo is captured. The photo is saved in a folder of the HoloLens device. This folder, exclusively created by DigiTAR, stores only the images captured within the tool. This segregation is essential since these photos are accompanied by important metadata, including the capture time and the user's position and orientation at the time of capture. The alignment of the 3D BIM model with the real world, achieved through the registration process and spatial anchoring, enables precise association of the captured images with their corresponding locations in the BIM model.

After capturing the images, users can perform pre-processing on them before uploading them to be utilized by the automated quality control system. For this purpose, DigiTAR establishes direct communication with the backend of the Visual Data Pre-processing module. This seamless integration streamlines the process of preparing the captured images for subsequent quality control analysis, ultimately enhancing the efficiency and accuracy of the entire construction quality management process.

4. RESULTS AND DISCUSSION

The first subsection presents and analyses the evaluation process of the trained Mask R-CNN for defect detection. In the second subsection, a use case of the overall quality control process is presented, endowed with the in-situ results' visualization and confirmation via the DigiTAR application.

4.1 Automated Quality Control Evaluation

The performance of the two models (concrete and steel case) was evaluated using the mean Average Precision (mAP), since this metric is often used to evaluate object detection models. Precision is the percentage of correct positive predictions for overall predictions. Specifically, mAP is the mean value of average precision (AP) for each object class (Guo et al., 2021). The concrete model and the railway model were evaluated for 20 and 10 epochs respectively. The mAP for the concrete model reached the value of 0.87, while the mAP for the railway defects was calculated 0.95. Figure 7 shows the ground truth and the respective predictions of the proposed models for some typical examples. For each example, the generated images contain the label prediction, the confidence level, and the respective mask. The label prediction indicates the identified defect type detected by the model. The confidence level represents the model's level of certainty or confidence in its prediction. The mask displayed in

[1] https://learn.microsoft.com/en-us/windows/mixed-reality/design/point-and-commit#hand-rays
[2] https://learn.microsoft.com/en-us/dynamics365/mixed-reality/guides/operator-gestures-hl2#air-tap
[3] https://learn.microsoft.com/en-us/windows/mixed-reality/design/hand-menu

the images highlights the specific region or area where the defect has been identified. This visual representation allows for a clear understanding of the location and extent of the detected defect within the image.

a) original images

b) predictions

Figure 7: Original images (a) and predictions (b) for crack, honeycomb, missing clamp, missing screw, and missing screw nut.

4.2 Use Case Demonstration

The case study is focused on a railway line across Munich, Germany. The old line had to be replaced with a new one. During the reconstruction phase, the site was checked for cracks, honeycombs and rail defects, such as missing clamps, missing screws, and screw nuts.

Regarding the AR visualization, the IFC and the OBJ files for the railway site were parsed within DigiTAR using the BIM model visualization process, which is described in Section 3.4.1. The registration process, that is described in Section 3.4.2, was conducted using a strategically positioned image target within the construction zone. Precise measurements in meters, obtained from the IFC file, guided the accurate placement of the image target on-site. After the registration process was completed, the 3D BIM model became aligned with the actual construction site. This alignment allowed for accurate integration of the digital model with the real-world environment. An on-site 3D BIM model visualization using DigiTAR is illustrated in Figure 8. Figure 9 illustrates the successful visualization of the QC outcomes on HoloLens 2 using DigiTAR.

Figure 8: Screenshot of the 3D BIM model, as visualized on-site with DigiTAR

Figure 9: Screenshot of QC tags visualized on-site with DigiTAR

The surveyor captured images of the new elements using the DigiTAR tool following the procedure described in Section 3.4.4. Also, the surveyor processed the images on-site and uploaded them for automatic quality control. Utilizing the power of the VQC tool, the uploaded images underwent comprehensive assessment, generating valuable results. These results were then promoted to the DigiTAR tool for on-site inspection and confirmation. By performing the air tap gesture on a QC tag, an overview of the related Visual QC results was displayed to the surveyor, as depicted in Figure 10.

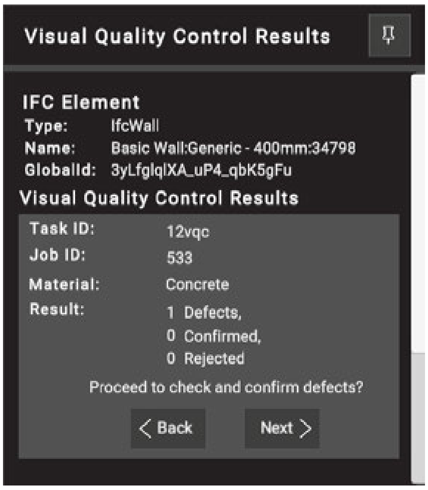

Figure 10: Overview visualization of the Visual QC results for a specific element

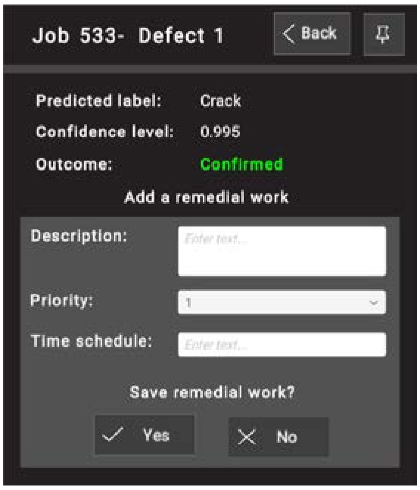

Figure 11: Menu to add remedial work to a QC result

By selecting the “Next” button in the menu in Figure 10, the surveyor could view details for the detected defect, as can be seen in Figure 12. The annotated image, the label of the detected defect and the confidence level were displayed (left figure in Figure 12). By selecting the “Original image” button, the surveyor could switch to viewing the original image that was sent for automatic visual quality control (right figure in Figure 12).

Upon confirming a detected defect, the surveyor was presented with the option to add a remedial work for the identified issue. The user-friendly menu to add a remedial work, as depicted in Figure 11, facilitated this process within the DigiTAR tool. To input the necessary information for the remedial work, the surveyor simply selected the relevant input fields on the menu. Upon selection, the HoloLens system keyboard was activated, allowing the user to type using hand gestures, making the data input intuitive and efficient.

The ability to process the remedial work in real-time within DigiTAR provided valuable advantages. It allowed for immediate consideration of mitigation measures and enabled rapid decision-making to address the identified defect effectively. This dynamic workflow streamlined the process of adding remedial works and contributed to enhanced project management and quality control.

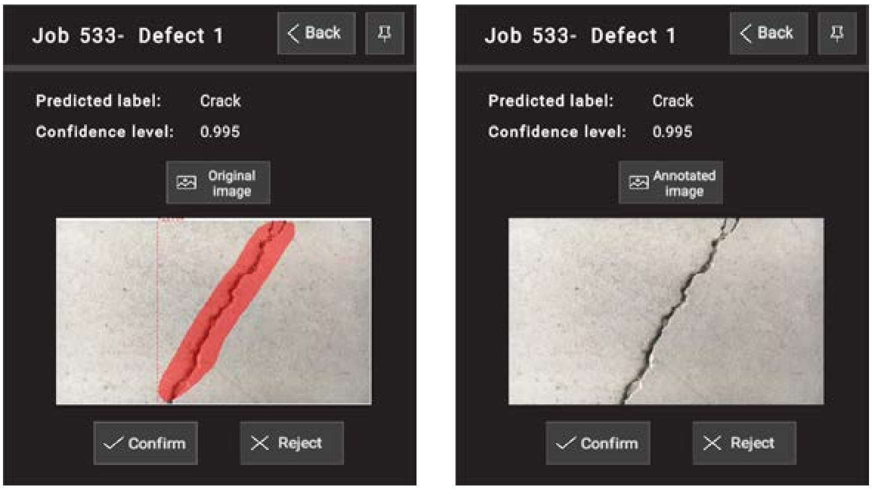

Figure 12: Visualization of a VQC result. The user can view the annotated (left) and the original image (right).

5. CONCLUSIONS AND FUTURE WORK

Embracing automation in the construction industry leads to improvements in the adaptability of the project and paves the way for greater innovation and advancement. As technology continues to evolve, leveraging automatic tools becomes a crucial aspect of staying competitive in the ever-changing construction landscape.

This study presents a framework for semi-automated visual quality control inspection in construction sites during the execution phase of the project. The framework incorporates two tools; the Visual Quality Control (VQC) tool and the Digital Twin visualization with Augmented Reality (DigiTAR) tool. The first tool incorporates a deep learning network trained to detect concrete and railway defects and serves as a backend service for automatic visual quality control on images captured at construction sites. The second tool leverages AR technology to display the visual quality control results on-site. The surveyors can inspect the detected defects in-situ and confirm or reject them. They are also prompted to add remedial works, if needed. DigiTAR displays the 3D BIM model of the construction site, i.e., the model is visualized to overlay the actual site, allowing construction professionals to interact with the BIM model in a dynamic and realistic manner using AR technology. This critical functionality enhances the overall understanding and visualization of the construction site, promoting better decision-making and coordination throughout the project lifecycle.

By combining automated quality control (performed by the VQC tool) with DigiTAR's intuitive interface and augmented reality capabilities, the surveyors gain real-time access to the quality control outcomes. This facilitates decision-making and enables prompt confirmation of the results, ensuring the construction project adheres to the highest quality standards. The seamless flow of data and information between the automatic quality control system and the DigiTAR tool enhances efficiency and accuracy, ultimately contributing to the successful execution of the construction project. The proposed framework aims to demonstrate how the synergy between cutting-edge technology and user-friendly interfaces can create a powerful asset for construction professionals in ensuring top-notch project outcomes. Future efforts will be dedicated to improving and expanding the model's training to encompass a wider range of defects. This endeavor aims to enhance the model's accuracy and efficiency in detecting various types of issues within the construction site. Additionally, the image acquisition procedure could be automatized and significantly improved utilizing drones and construction site inspection robots (such as Spot robots that are used for automated laser scanning), since our framework has been developed to support this functionality. Finally, there is a plan to equip the model with the capability to detect defects on video streams and empower DigiTAR to also display the video captures. This enhancement will enable real-time monitoring and analysis of ongoing construction activities, empowering construction professionals to address potential issues as they arise.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Union’s Horizon 2020 Research and Innovation Programme through COGITO project under Grant Agreement No. 958310. Special thanks to Olympia Odos and to Rhomberg Sersa Rail Group for providing UAV images of concrete defects and images of railway steel defects, respectively. Special thanks to Rhomberg Sersa Rail Group, and especially Katharina Leer, for their valuable participation in the use case demonstration.

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A COMPARATIVE STUDY OF DEEP LEARNING MODELS FOR SYMBOL DETECTION IN TECHNICAL DRAWINGS

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ABSTRACT: *Symbols are a universal way to convey complex information in technical drawings since they can represent a wide range of elements, including components, materials, or relationships, in a concise and space-saving manner. Therefore, to enable a digital and automatic interpretation of pixel-based drawings, accurate detection of symbols is a crucial step. To enhance the efficiency of the digitization process, current research focuses on automating this symbol detection using deep learning models. However, the ever-increasing repertoire of model architectures poses a challenge for researchers and practitioners alike in retaining an overview of the latest advancements and selecting the most suitable model architecture for their respective use cases. To provide guidance, this contribution conducts a comparative study of prevalent and state-of-the-art model architectures for the task of symbol detection in pixel-based construction drawings. Therefore, this study evaluates six different object detection model architectures, including YOLOv5, YOLOv7, YOLOv8, Swin-Transformer, ConvNeXt, and Faster-RCNN. These models are trained and tested on two distinct datasets from the bridge and residential building domains, both representing substantial sub-sectors of the construction industry. Furthermore, the models are evaluated based on five criteria, i.e., detection accuracy, robustness to data scarcity, training time, inference time, and model size. In summary, our comparative study highlights the performance and capabilities of different deep learning models for symbol detection in construction drawings. Through the comprehensive evaluation and practical insights, this research facilitates the advancement of automated symbol detection by showing the strengths and weaknesses of the model architectures, thus providing users with valuable guidance in choosing the most appropriate model for their real-world applications.*

KEYWORDS: *Computer Vision, Technical Drawings, Symbol Detection, Comparative Study*

1. INTRODUCTION

Symbols pose an efficient and space-saving way of conveying complex information, enabling understanding across languages due to their standardized appearance. They find application in diverse contexts, such as street signs (Gudigar et al., 2016), maps (Huang et al., 2023), or technical drawings (Elyan et al., 2020b). For instance, in construction drawings symbols can represent architectural components, plumbing fixtures, elevation markings, and more, making accurate identification of the symbols essential for understanding the entire drawing. The importance of precise symbol detection becomes even more apparent when algorithms are used to understand the technical drawings automatically, e.g., for their digitization. Therefore, research has focused on developing effective and accurate algorithms for locating and classifying symbols in technical drawings. Ah-Soon (1998) proposed to adapt Messmer's algorithm for symbol recognition in architectural drawings using graph matching. The drawing is first vectorized, followed by the extraction and merging of geometric features for each symbol, and clustering similar symbols by type. In a separate work, Adam et al. (2000) developed an orientation and scale invariant method for recognizing symbols in technical documents. Their algorithm is based on the Fourier-Mellin transform, which extracts features used to label the symbols through a classifier.

Most of this research focuses on traditional image analysis techniques, such as vectorization and feature engineering. However, with the advent of efficient deep learning approaches, such as convolutional neural networks (CNN), the research community's interest has shifted to use such models for localizing and classifying symbols in technical drawings. Ziran and Marinai (2018) leverages the object detection networks Faster R-CNN and Single Shot Detector (SSD) to detect symbols representing objects such as furniture, doors, and windows in architectural floor plans. In the context of piping and instrumentation diagrams (P&IDs), Mani et al. (2020) develops a custom CNN to classify components in the P&IDs. The proposed network is trained to classify patches cropped from the overall drawing into three classes: tag symbol, component symbol, or no symbol. When the network detects a symbol within a patch, the corresponding detection is projected back onto the original drawing. In a different approach for P&IDs, Elyan et al. (2020a) employs the YOLO architecture for symbol detection. Additionally, the authors propose a method based on generative adversarial networks to mitigate the issue of class imbalance in technical drawings. Class imbalance occurs when the number of instances per symbol class shows significant variation. A novel approach to enhance symbol detection by inferring the symbol orientation is

Referee List (DOI: 10.36253/fup_referee_list)
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introduced by Faltin et al. (2023b). The authors leverage human pose detection networks, specifically Mask R-CNN and YOLOv7Pose, to achieve accurate symbol pose estimation in construction drawings.

While the proposed approaches already utilize several different detection models, the overall field of object detection has experienced rapid growth, leading to the emergence of numerous model architectures (Zaidi et al., 2022). Researchers and industry practitioners alike face the difficult task of selecting the most appropriate architecture for their specific applications. This becomes especially difficult when other critical requirements such as training time, inference time, or model size must be considered in addition to detection accuracy. For instance, in real-time applications, faster inference time may be prioritized, while in resource-constrained environments, smaller model sizes may be important. Therefore, researchers and practitioners need to conduct thorough evaluations of the various object detection models to make an informed decision.

Previous research has compared different model architectures for different applications to aid in model selection. However, to the best of the authors' knowledge, there is no study that directly compares detection models for symbol detection in pixel-based drawings. Nevertheless, related publications have conducted comparison studies in various other domains. For instance, Brößner et al. (2022) compares nnUNet with the transformer-based Swin-UNet for bone segmentation in ultrasound images, finding that both networks are similarly applicable to the task. In another study, Wang et al. (2023) conducts a comparison for different backbones such as ResNet, Swin, and ViTAEv2, by pre-training them on a large dataset of satellite images to later test them on different down-stream tasks, such as image segmentation or object detection. The authors discover that the transformer-based models show competitive results compared with the CNN models. In particular, ViTAEv2 achieves the highest performance on the different tasks. Moutik et al. (2023) compares several models based on CNNs, transformers, and hybrid approaches, to recognize human actions in video data. This study concludes that the CNN- and transformer-based models perform similarly, both with their strengths and weaknesses, but overall, the hybrid methods achieve the best results.

Our research contributes to this broad research area by providing a comprehensive analysis of state-of-the-art object detection models and evaluating them based on several criteria for symbol detection in construction drawings. The remainder of the paper is structured as follows: Section 2 presents the methodological design of the comparative study conducted and details of the datasets used. Subsequently, in Section 3, we present and discuss the results of our comparative study, shedding light on the performance of different detection models. Finally, Section 4 summarizes the results and provides possible directions for further research in this area.

2. METHODOLOGY

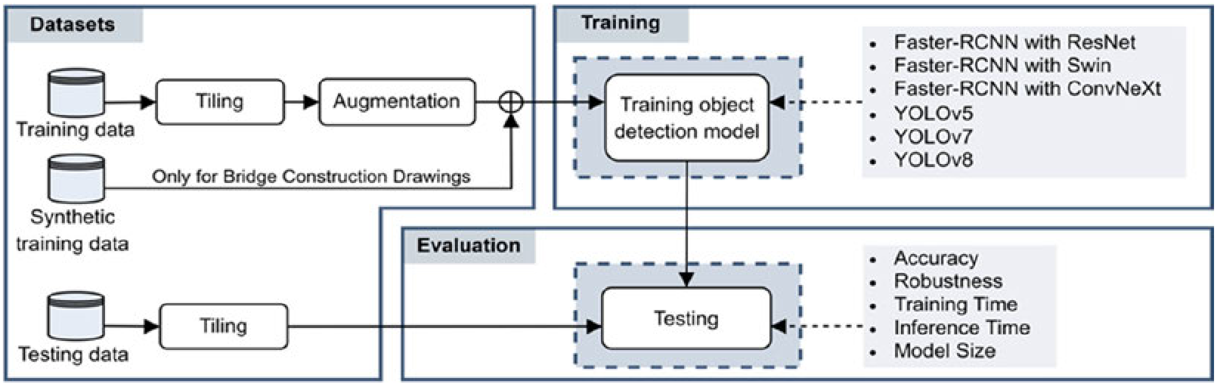

Fig. 1: Overview of the methodology used in the comparative study.

The structure of this comparative study is shown in Fig. 1. Real data is collected and annotated to train and test the selected models. In addition, synthetic data is generated to extend the dataset. The models are trained with a combination of real and synthetic data, while only real data is used for testing. Section 2.1 provides a detailed description of the datasets. The comparison includes six different network architectures: YOLOv5 (Jocher et al., 2022), YOLOv7 (Wang et al., 2022), YOLOv8 (Jocher et al., 2023), and Faster R-CNN (Ren et al., 2017) with three different backbones namely ResNet (He et al., 2016), Swin (Liu et al., 2021), and ConvNeXt (Liu et al., 2022). A brief introduction to the compared network architectures is presented in Section 2.2. In order to comprehensively assess the models, they are evaluated with respect to five criteria, i.e., accuracy, robustness, training time, inference time, and model size, which are explained in detail in Section 2.3.

2.1 Datasets

To obtain a meaningful comparison, the models are trained and tested on two distinct datasets representing different sub-sectors of the construction industry: bridge construction drawings and floor plans. The *bridge*-dataset comprises 15 real construction drawings with approximately 10.000 x 6.000 pixels dimensions. To make the large dimensions of the drawings manageable for the models, tiling is used to divide the drawings into patches. The drawings contain three types of symbols: section symbols, elevation markers, and dimension symbols (cf. Fig. 2). The size of these symbols varies from 20 to 300 pixels, which is relatively small compared to the overall size of the drawing. Consequently, the models must be able to produce meaningful feature representations even for small objects. To investigate this, the study explores different patch sizes to examine the influence of the symbol-to-image size ratio. Therefore, three patch sizes are considered: 256 pixels, 512 pixels, and 1024 pixels. This results in three data subsets named *bridge_256*, *bridge_512*, and *bridge_1024*, containing 2120, 1185, and 543 patches, respectively.

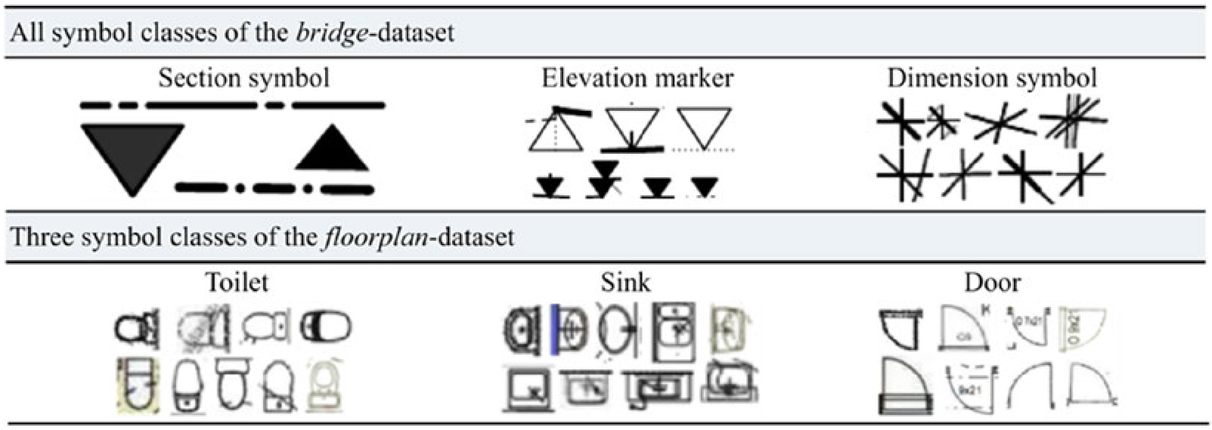

Fig. 2: Example illustration of some representative symbols selected from the datasets.

Since the number of patches is still quite limited, additional synthetic data is generated based on the procedure introduced by Faltin et al. (2022a). Lastly, to investigate the influence of the quantity of training data on the model's performance for the *bridge*-dataset, a reduced data subset called *bridge_1024_red* is created, which comprises only 10% of the original data subset *bridge_1024*. Table 1 gives an overview of the composition of all datasets.

Table 1: Overview of the composition of the data subsets. Synthetic data is only used for training and validation.

	No. training images	No. synthetic training images	No. validation images	No. synthetic validation images	No. testing images
bridge_256	5611	1500	993	250	316
bridge_512	3179	1500	544	250	192
bridge_1024	1477	1500	250	250	94
bridge_1024_red	130	170	25	25	94
floorplan_1024	10294	0	1800	0	750

On the other hand, the *floorplan*-dataset consists of 5000 fully annotated floor plans of residential buildings sourced from the CubiCasa-dataset (Kalervo et al., 2019). The majority of the drawings in this dataset are similarly sized ranging between 500 and 2000 pixels, therefore they are resized uniformly to 1024 pixels (*floorplan_1024*). The drawings distinguish eight different symbol classes: window, door, electrical appliance, toilet, sink, sauna bench, fireplace, and bathtub. Fig. 2 illustrates the high intra-class variation among these symbols, which requires effective generalization of the object detection models to handle the diverse styles.

2.2 Object Detection Models

In this study three single-stage detection models, namely YOLOv5, YOLOv7, and YOLOv8 are compared with three two-stage detection models. Each two-stage model modifies the Faster R-CNN architecture by replacing the backbone while keeping the region proposal network and detection head unaltered. The selected backbones are ResNet, ConvNeXt, and Swin. In this section, a short overview of the different architectures is given.

The YOLO model series is known for its high detection performance and fast inference speed. Both YOLOv7 and YOLOv8 are extensions of YOLOv5 but incorporate different ideas such as anchorless detection and different convolutional blocks to enhance the base model's performance.

In comparison, ResNet is a well-established CNN-based image classification network commonly used as the backbone architecture for Faster R-CNN. On the other hand, the Swin backbone is a transformer-based architecture, building upon the concept of the visual transformer introduced by Dosovitskiy et al. (2020). Swin addresses the challenges of adapting transformers to the image domain by employing a hierarchical architecture with shifting attention windows. Lastly, ConvNeXt progressively modernizes the basic ResNet architecture by incorporating key components of visual transformers into the CNN-based architecture.

For each of the chosen model architectures, the base size and the smallest version, referred to as tiny, are compared. This investigates whether equivalent results can be obtained with smaller model sizes. In general, larger models can extract more meaningful features due to their increased complexity, allowing them to handle challenging tasks while, in contrast, making them prone to overfit. The smallest versions are ResNet-50, Swin-Tiny, ConvNeXt-Tiny, YOLOv5n, YOLOv7-tiny, and YOLOv8n, while the base-versions are ResNet-101, Swin-Base, ConvNeXt-Base, YOLOv5m, YOLOv7, and YOLOv8m.

2.3 Evaluation

To provide a comprehensive overview of the strengths and weaknesses of each model, they are evaluated based on five criteria: accuracy, robustness, training time, inference time, and model size. A detailed explanation of each criterium is given in the remainder of this section:

2.3.1 Accuracy

Accuracy measures the model's ability to correctly locate and classify the symbols within the drawing. To assess the accuracy the standard metric of mean average precision (mAP) as defined by Padilla et al. (2021) is utilized, as it considers the precision and recall, evaluated at certain levels of intersection over union (IoU). While the precision indicates the proportion of accurate predictions made by the model among all the predictions, the recall denotes the proportion of correct predictions compared to the total number of ground-truth boxes available. Lastly, the IoU quantifies the overlap between a prediction and the ground-truth bounding box, measuring the model's localization accuracy.

2.3.2 Robustness

Obtaining and annotating extensive training data is time-consuming, resulting in data scarcity in many cases. Hence, it is highly desirable to have a robust object detection network, which means it performs reasonably well even with limited training data. The model is trained with 90% reduced training data to evaluate robustness. After training, the network's performance is tested with the full test dataset using the mAP metric. This enables an estimate of the accuracy decrease when training data is significantly limited.

2.3.3 Training time

Training time measures the physical time required for the model to reach a plateau, indicating that no further improvement is expected. This is particularly important in applications with limited computational resources or where the model is regularly retrained. While the training time may vary depending on the hardware used, in this study all models are trained on the same GPU to ensure comparability.

2.3.4 Inference Time

The inference time quantifies how long it takes for the model to make a single prediction, making it a vital metric for real-time applications.

2.3.5 Model size

Model size describes the memory requirements of the model and is a crucial factor that directly affects various aspects of model performance. Smaller models usually have a smaller number of parameters, leading to shorter inference times. However, extremely small models may not have the necessary complexity to handle the given task effectively. Therefore, it is important to carefully select the appropriate model size to achieve optimal performance.

3. RESULTS & DISCUSSION

To perform the comparative study, the models are trained by running three Nvidia A100-SXM4-40GB GPUs. The two-level networks are available pre-trained solely on the ImageNet-1K dataset, which is a subset of the larger ImageNet dataset (Deng et al., 2009). Conversely, the YOLO models are available pre-trained exclusively on the MS COCO dataset (Lin et al., 2014). The AdamW (Loshchilov & Hutter, 2017) optimizer is employed with a batch size of 64 and an initial learning rate of 0.0001 for backpropagation. The maximum number of epochs is set to 400, but early stopping is utilized to prevent overfitting. In order to increase the overall quantity and diversity of the training data, data augmentation techniques such as flipping, rotation, scale, or translation are utilized for all data subsets. The results are presented and discussed in the following sections based on the different evaluation criteria.

3.1 Results for Accuracy

Table 2 shows the results of the comparative study focusing on symbol recognition accuracy. To evaluate the symbol detection performance with the mAP metric, an IoU threshold of 0.5 (mAP@0.50) is appropriate for most use cases. Nevertheless, the more stringent mAP@0.50:0.95 is also used in this study to evaluate the models more comprehensively. For the bridge dataset, ConvNeXt-B achieves the highest mAP@0.50 score of 0.996 on 512 x 512 pixel patches, closely followed by ResNet-101, Swin-T, and Swin-B, all obtaining a score of 0.992 on 1024 x 1024 pixel patches. This suggests that the symbol-to-image size ratio is not critical, as the models accurately detect smaller symbols even on larger patches. But on the contrary, performance generally declines with smaller patch sizes, with the lowest results observed on 256 x 256 pixel patches. This demonstrates the importance of context, as the models must consider each symbol's surrounding space to locate and classify it properly. This is consistent with the observations of Lim et al. (2019), who similarly emphasized the importance of context when dealing with small objects.

Table 2: Performance results of the detection models on the *bridge*- and *floorplan*-dataset. The bold fonts indicate the best results for the respective data subset, while the asterisk indicates the best results for the specific dataset.

	Bridge-dataset						*Floorplan*-dataset	
	256 x 256 Pixel		512 x 512 Pixel		1024 x 1024 Pixel		1024 x 1024 Pixel	
	$mAP_{0.50}^{IoU}$	$mAP_{0.50:0.95}^{IoU}$	$mAP_{0.50}^{IoU}$	$mAP_{0.50:0.95}^{IoU}$	$mAP_{0.50}^{IoU}$	$mAP_{0.50:0.95}^{IoU}$	$mAP_{0.50}^{IoU}$	$mAP_{0.50:0.95}^{IoU}$
ResNet-50	0.912	0.739	0.973	0.815	0.986	0.833	0.771	0.492
ResNet-101	0.927	0.743	0.980	0.827	**0.992**	0.830	0.776	0.485
Swin-T	0.945	0.769	0.961	0.801	**0.992**	0.846	0.789	0.517
Swin-B	**0.950**	0.742	0.978	0.834	**0.992**	0.847	0.799	0.518
ConvNeXt-T	0.934	0.763	0.992	0.862	0.991	0.855	0.795	0.527
ConvNeXt-B	0.934	0.786	***0.996**	0.864	0.991	0.862	0.806	0.524
YOLOv5n	0.884	0.578	0.868	0.615	0.912	0.645	0.649	0.379
YOLOv5m	0.886	0.704	0.951	0.799	0.973	0.838	0.761	0.510
YOLOv7-tiny	0.884	0.648	0.924	0.675	0.949	0.686	0.763	0.474
YOLOv7	0.934	0.705	0.956	0.786	0.967	0.748	***0.816**	0.551
YOLOv8n	0.921	0.715	0.890	0.705	0.965	0.794	0.717	0.454
YOLOv8m	0.938	0.814	0.965	0.854	0.982	0.891	0.805	0.570

Regarding mAP@0.50:0.95, ConvNeXt-B still achieves the best results with 0.864. Conversely, YOLOv5n is the weakest performer in both mAP@0.50 and mAP@0.50:0.95, likely due to its lower model complexity affecting its ability to handle the complex symbol detection task.

For the *floorplan*-dataset, YOLOv7 leads by a significant margin (0.816), followed by ConvNeXt-B (0.806) and YOLOv8m (0.805). However, when considering mAP@0.50:0.95, YOLOv8m outperforms YOLOv7 with a notable gap. The general accuracy on the floor plans is lower compared to that of the bridge drawings. This discrepancy may be due to a larger number of symbol classes or a wider variety of symbol styles in the *floorplan*-dataset.

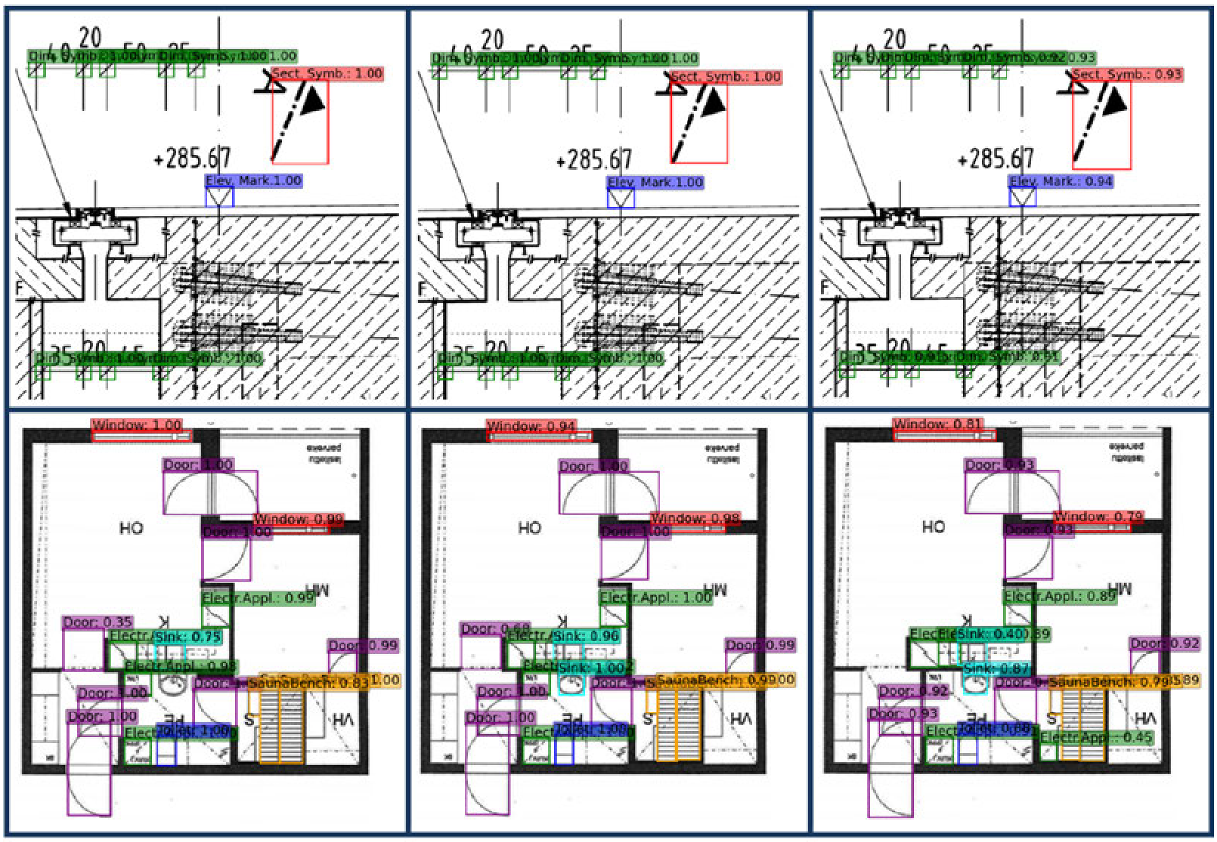

Fig. 3: Predictions of the base models of Swin (left), ConvNeXt (center), and YOLOv8 (right) on a patch from the *bridge*-dataset (top) and the *floorplan*-dataset (bottom).

Overall, larger and newer models perform better when accuracy matters. However, no significant difference in detection accuracy is seen between transformer-based and modern CNN-based networks. Despite that, the YOLO models tend to achieve lower mAP values than the two-stage models. This might be due to the YOLO model's smaller size. One exception is the YOLOv8m model, which achieves the highest values of all YOLO models and sometimes even outperforms the two-stage models.

3.2 Results for Robustness

The results for the reduced training dataset are presented in Table 3. While ConvNeXt-B shows the highest mAP score on the full training dataset, its performance declined by 25% when trained on the reduced dataset. It is also noteworthy that YOLOv5n, which already performed the worst, showed the largest decrease with 51%. On the other hand, YOLOv7 is quite robust to reduced training data, showing an 18% drop with mAP@0.50:0.95 score of 0.614. It is followed by the second most robust network ResNet-101 with a decrease of 26%.

3.3 Results for Training Time, Inference Time & Model Size

Table 3 shows the training time, inference time, and model size of the compared object recognition networks. Among them, YOLOv8n has the shortest training time with 0.51 hours on average, while still achieving promising results, as shown in Table 2. On the other hand, the transformer-based Swin-B network requires the longest training time. This is probably due to the computationally intensive attention mechanism used by the Swin network. In terms of inference time, the YOLO models demonstrate superior performance compared with the two-stage models. Specifically, YOLOv7-tiny achieves the fastest inference time, averaging 1.6 milliseconds per image, followed by YOLOv7 with 6.4 milliseconds per image. Surprisingly, despite its smaller network size, YOLOv5n does not display the fastest inference time. It is worth noting that even the largest network, ConvNeXt-B, has a relatively small memory requirement of 400 MB.

Table 3: Performance results on the reduced *bridge*-dataset as well as training time, inference time, and model size. The bold fonts indicate the best results for the respective column.

	bridge_1024_red				
	$mAP_{0.50}^{IoU}$	Performance decrease	Training time in hrs. averaged	Inference in ms/img on 1024 x 1024 pixels	Model size in MB
ResNet-50	0.590	-31%	2.58	52.9	157.97
ResNet-101	0.611	-26%	3.21	55.3	230.62
Swin-T	0.635	-25%	5.19	70.4	170.95
Swin-B	0.602	-29%	7.52	109.9	397.56
ConvNeXt-T	0.633	-26%	4.20	64.5	171.88
ConvNeXt-B	0.645	-25%	5.51	104.2	400.27
YOLOv5n	0.319	-51%	0.82	12.9	**7.12**
YOLOv5m	0.541	-35%	2.67	17.8	80.77
YOLOv7-tiny	0.491	-28%	1.12	**1.6**	22.94
YOLOv7	**0.614**	**-18%**	3.15	6.4	139.21
YOLOv8n	0.570	-28%	**0.51**	12.9	11.49
YOLOv8m	0.672	-25%	2.49	18.3	98.65

In summary, it is important to find a balance between model size and accuracy. Smaller models may perform worse and models that are too large may overfit on the training data. Therefore, when choosing an appropriate model size, an optimal trade-off between model complexity and performance must be made based on the specific requirements of the application.

4. CONCLUSION

This paper provides a comprehensive comparison of six object detection models employed for the task of symbol detection in pixel-based construction drawings. The evaluated models include YOLOv5, YOLOv7, YOLOv8, and Faster R-CNN, equipped with three different backbones, i.e., ResNet, Swin, and ConvNeXt. For each architecture the smallest and baseline model size are employed, resulting in a total of twelve compared models. The evaluation is conducted along five key criteria, namely accuracy, robustness, training time, inference time, and model size. This offers valuable insights to guide the selection of appropriate models for diverse use cases and their specific requirements. The models are trained and tested on bridge construction drawings as well as floor plans representing two common sub-sectors of the construction industry.

Among the evaluated models, ConvNeXt shows the highest accuracy in the *bridge*-dataset, which makes it the best choice for detecting small symbols with low variance. On the other hand, when a high variance of symbol style is present, YOLOv7 or YOLOv8 are more suitable choices. Notably, YOLOv7 also proves robust when trained with reduced data, therefore making it superior to YOLOv8. Overall, the YOLO models generally have lower training and inference times, which can be directly linked to their smaller model size. Overall, the more recent models, including YOLOv8, Swin, and ConvNeXt, show comparably high accuracy, suggesting that significant improvements in the future will be limited. Nevertheless, promising research directions such as self-supervised learning (Jaiswal et al., 2021) and active learning (Schmidt et al., 2020) are expected to advance training efficiency by reducing the amount of training data required or the manual annotation effort. Moreover, expanding upon the proposal by Elyan et al. (2020a) for generating synthetic data through deep learning models, employing new methods such as stable diffusion (Rombach et al., 2022), could improve detection results even more, mitigating the scarcity of real data.

The results of our study provide valuable insights for the future development of symbol detection research, enabling further exploration of model performance on other technical drawing types, such as P&IDs. Investigating hybrid models that combine transformer- and CNN-based architectures represents another promising direction for future research.

5. ACKNOWLEDGMENTS

This research is being conducted as part of the BIMKIT project, which is funded by the German Federal Ministry of Economics and Climate Protection. Furthermore, we would like to thank Lisa Freiin von Rössing for her valuable contributions to this study.

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TOPOLOGICAL RELATIONSHIP MODELLING FOR INDUSTRIAL FACILITY DIGITISATION USING GRAPH NEURAL NETWORKS

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ABSTRACT: There is rising demand for automated digital twin construction based on point cloud scans, especially in the domain of industrial facilities. Yet, current automation approaches focus almost exclusively on geometric modelling. The output of these methods is a disjoint cluster of individual elements, while element relationships are ignored. This research demonstrates the feasibility of adopting Graph Neural Networks (GNN) for automated detection of connectivity relationships between elements in industrial facility scans. We propose a novel method which represents elements and relationships as graph nodes and edges respectively. Element geometry is encoded into graph node features. This allows relationship inference to be modelled as a graph link prediction task. We thereby demonstrate that connectivity relationships can be learned from existing design files, without requiring domain specific, hand-coded rules, or manual annotations. Preliminary results show that our method performs successfully on a synthetic point cloud testset generated from design files with a 0.64 F1 score. We further demonstrate that the method adapts to occluded real-world scans. The method can be further extended with the introduction of more descriptive node features. Additionally, we present tools for relationship annotation and visualisation to aid relationship detection.

KEYWORDS: *BIM, Digital twin, GNN, machine learning*

1. INTRODUCTION

Ageing industrial facilities often lack essential documentation, resulting in sub-optimal maintenance and breakdowns. Digital twins remedy this and assist in the operation and maintenance of industrial facilities. However, generating twins for existing facilities is a laborious and time-intensive process that outweighs the perceived benefits offered by the twins. (Agapaki et al., 2018). While this has resulted in significant interest in automation, current approaches merely segment elements and model their geometry. However, industrial facilities are composed of a vast number of interconnected elements of various categories; thus, the identification of their connectivity relationships is a crucial, yet challenging step in the digitisation process.

The prevalent methodology for constructing geometric DTs from existing facilities, known as "Scan-to-BIM" (Tang et al., 2010) consists of the following steps: (1) raw data collection, (2) data preparation, (3) geometric modelling, and (4) semantic enrichment of the model. The focus of this paper is the final step.

Semantic enrichment' refers to the incorporation of various forms of additional information into a digital twin to enhance its value. Some common examples are element relationships, material information, damages to elements, and code compliance information. There are various types of 'element relationships' within industrial facilities. Tang et al (Tang et al., 2010) identifies three commonly found relationship types. Namely, topological relationships (e.g., a pipe being connected to an elbow), aggregation relationships (e.g., a pipe being within the HVAC (Heating, Ventilation and Air Conditioning) system) and containment relationships (e.g., a window belonging to a wall). This paper focuses on topological relationships.

Topological relationships between various elements of a facility are a key component of its documentation. For instance, when diagnosing faults within building systems (Tang et al., 2010), carrying out maintenance tasks, or checking for code compliance (Bloch & Sacks, 2020), topological relationships must be identified in advance. They are also crucial when analysing sub-systems within a plant, which assists maintenance and monitoring.

A variety of industry tools such as Trimble RealWorks, Leica Cyclone, ClearEdge3D EdgeWise are used in the DT construction process. Currently, element relationships modelling between elements is largely a manual process with industry tools providing limited automation. Tools such as EdgeWise can connect adjacent pipes, but not other piping elements. AVEVA E3D and PointSense offer the ability to derive pipe branches but require user guidance through point picking. A feature comparison of popular tools is given in table 1 (Son et al., 2015). The requirement of manual guidance throughout the modelling process is one of the primary pitfalls of current software solutions, necessitating significant expert labour.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Haritha Jayasinghe, Ioannis Brilakis, *Topological Relationship Modelling for Industrial Facility Digitisation Using Graph Neural Networks,* pp. 887-894,

Table 1. Comparison of automation features and pipe modelling functions (SA=Semi-automated, FA=Fully-automated, NA=Not-available, Source: (Son et al., 2015)

Task	Trimble RealWorks	Leica Cyclone	ClearEdge3D EdgeWise
Automation features			
Pipe Detection	SA	FA	FA
Part Recognition (e.g., elbows, tees)	FA	NA	FA
Model Creation	FA	FA	FA
Pipe modelling functions			
Straight pipe	FA	FA	FA
Elbow	NA	NA	FA
Tees	NA	NA	FA

This paper proposes a novel method for automatically identifying topological relationships between elements within industrial facility models using GNNs. We demonstrate our model's performance both on synthetic and real-word data. Furthermore, we present tools for relationship visualisation and annotation to aid in the relationship detection process. Crucially, this research demonstrates the applicability of graph inference for element relationship inference in BIM.

2. BACKGROUND

Current literature on industrial facility DT construction predominantly encompasses the first three steps of the Scan-to-BIM process. Annotated point cloud datasets such as CLOI contains elements from classes such as Channels, Valves, I-beams, Flanges, Elbows, Cylinders and Angles (Agapaki et al., 2019). A prominent instance segmentation method utilizes CLOI-NET, a modified PointNet++ based neural network to identify element point clusters using the above dataset. This achieves 73.2% mean precision and 71.1% mean recall over all classes. However, results for more complex shapes such as flanges are considerably lower, especially in the presence of occlusions. Another approach proposes ResPoint++, which uses an encoder-decoder structure trained on I-Beams, R-Beams, pumps, pipes, and tanks (Yin et al., 2021). Xie et al proposes PipeNet for modelling straight pipes via centreline prediction (Xie et al., 2023). Once element point clusters are retrieved, they are geometrically modelled with approaches such as CAD model matching (Agapaki & Brilakis, 2022). However, the final semantic segmentation step, particularly in the form of relationship inference is yet unsolved, in industrial facilities as well as in other domains. Moreover, scan datasets with annotated relationships currently do not exist.

Traditionally, element relationships are defined with various data schemas such as IFC. However, graph representations of IFC models have recently become prominent due to their ability to query information more effectively. In a graph representation, each element is represented by a graph node. Relationships between elements are depicted by edges. Graphs are well suited for the representation of building information as both spatial and non-spatial information can be stored as node or edge properties within a graph (Ismail et al., 2018).

Previous attempts at automated detection of element relationships rely on hard coded rules. Nguyen et al. proposes an algorithmic approach to inferring relationships such as adjacency, containment, intersection, and connectivity from CAD models of elements (Nguyen et al., 2005). This requires complete CAD models without occlusions and is constrained by many assumptions. Another approach infers connecting tees and elbows based on pipe centrelines to predict pipelines (Oh & Kwang, 2021). Hard coded rules are unique to their domain. Thus, these approaches cannot scale to various domains, and are limited to a few common scenarios. To our knowledge, no published work exists that attempts to derive relationship information between various elements a laser scan.

Such a task would require an understanding of the nature of element relationships within an environment. For instance, the existence of a pipe and an elbow in proximity and in alignment suggests that the two elements are linked. There is a diverse and non-exhaustive set of such instances where relationships can be inferred, especially in the presence of occlusions and barriers such as walls. Furthermore, these vary between domains; the types of relationships in a bridge are vastly different from those in an industrial facility. Thus, rule-based approaches to relationship inference tend to perform poorly. We posit that a method of automatically learning the nature of relationships in a particular domain is better suited for this use case. In particular, we focus on GNNs, which are geometric deep learning approaches capable of learning directly from graphs.

GNN architectures can be split into spatial and spectral GNNs. Spatial GNNs such as GraphSAGE (Hamilton et al., 2017) and Graph attention Networks (GAN) (Veličković et al., 2017) create vector embeddings of graph nodes and aggregate features of adjacent nodes. In contrast, spectral GNNs such as Graph Convolution Networks (GCN)

(Kipf & Welling, 2016) are based on graph message passing. Other influencing factors include size of the graph and type of task. Tasks can be broadly categorized into three types: node classification, link prediction and graph classification. The choice of architecture for a particular task is influenced by a variety of factors. For instance, GraphSAGE and GCN are by default suited for graphs without edge features. Furthermore, they both behave as inductive frameworks, allowing them to scale to nodes that are unseen during the training process. However, inductive frameworks are unable to perform prediction on a completely edgeless new node, as information cannot be propagated in the absence of edges. Methods such as Edgeless-GNN (Shin et al., 2021) address this shortcoming by introducing pseudo edges based on similarities in node features. These edges ensure message propagation to new nodes.

There are very few applications of GNNs in the buildings domain. Buruzs et al. and Wang et al. both utilize graph representations of IFC models for the task of room type classification. They utilize a GCN and a modified version of GraphSAGE architecture respectively (Buruzs et al., 2022; Wang et al., 2022). They both model the task as a node classification problem and focus on indoor living spaces. Some of the edge features used within the graph representation include type of connection (e.g., Door vs wall) and material of connection (wooden vs metal door), while some of the node features include volume, height, oriented bounding box dimensions etc. The above methods demonstrate the suitability of graph learning in BIM.

The above findings demonstrate that we do not yet know how to automatically detect relationships between industrial facility elements. We merely know how to identify individual elements in isolation, but a digital twin should represent the connectivity and interactions of the system. The aim of this work is to address this gap in knowledge by answering the research questions; (a) Which strategy to utilize for automated inference of topological element relationships with high precision and recall? And (b) How to train an element relationship inference model in the absence of annotated relationship datasets?

3. PROPOSED SOLUTION

We propose a method for automated topological relationship detection between elements. The scope of this research is limited to cylinders, elbows, tees, and flanges. These elements account for a majority of the modelling workload (Agapaki et al., 2018).

Segmented element point clusters of existing industrial facilities are the input data source. These individual point clusters are extracted from a scan using an existing instance segmentation method such as CLOI-NET. Elements and their relationships are represented in the form of a graph. Each element is modelled as a graph node, and its geometric features and element class are encoded into a graph node feature vector. Relationships are represented by edges. Relationship detection is modelled as an edge prediction task and a GNN is trained for this purpose.

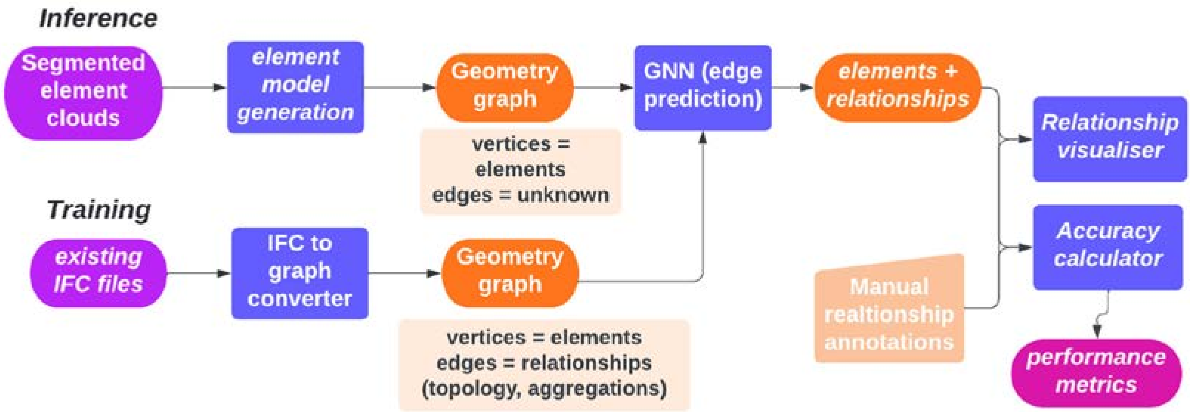

Figure 1. Overview of the proposed solution

Element geometry information is encoded into graph node features. These features are used by the GNN to learn the influence of element geometry on connectivity between elements. A more descriptive node feature provides additional information to the GNN. Possible features include: (a) minimum oriented bounding boxes (MOBB) of elements, (b) element-specific parameters such as axis, radius etc., (c) sampled subset of points, and (d) learned feature vectors. Oriented bounding boxes can be easily derived but are limited to crude information regarding element geometry and position. These are heavily affected by outliers and errors in instance segmentation. In contrast, element specific features are more difficult to extract from point clouds, but are more descriptive, especially for shapes such as elbows. They can represent geometries accurately with few parameters. Examples include element position (e.g., centre point), orientation (e.g., cylinder axis) and element geometry (e.g., radius, length). Element parameters of simpler shapes such as cylinders may be extracted using methods such as RANSAC, but more complex shapes such as elbows can prove challenging. Yet another approach would be to encode the element point cluster into a feature vector. Such an encoding may be generated automatically by using a deep learning approach such as PointNet (Qi et al., 2016) and would theoretically be capable of robustly representing the element.

Manual annotation of a relationship dataset to train the GNN would require a significant amount of time and labour. Thus, we generate training data from design files which contain element relationship information. In terms of GNN architecture, we opt for GraphSAGE, as it is (a) capable of inductive learning, (b) suited for link prediction, (c) scales linearly in the number of graph edges and (d) has been successfully utilised for previous BIM applications (Wang et al. 2022).

4. RESEARCH METHODOLOGY

This research is designed upon the assumption that topological relationships between elements can be inferred from their geometric features, and that the nature of such relationships can be learned by a neural network. We further assume that the data loss from compressing point cloud instances to node features does not significantly affect the ability of a GNN to identify element relationships.

The dataset used for training is composed of design files for an offshore Liquid Natural Gas hub in NavisWorks format. The subset utilized for experimentation comprises of two sub sections of the site containing around 37,000 elements with around 31,000 unique topological relationships (Figure 2). Element relationships were extracted using a python script through the NavisPythonShell plug-in and geometries were extracted by the NavisTools plug-in.

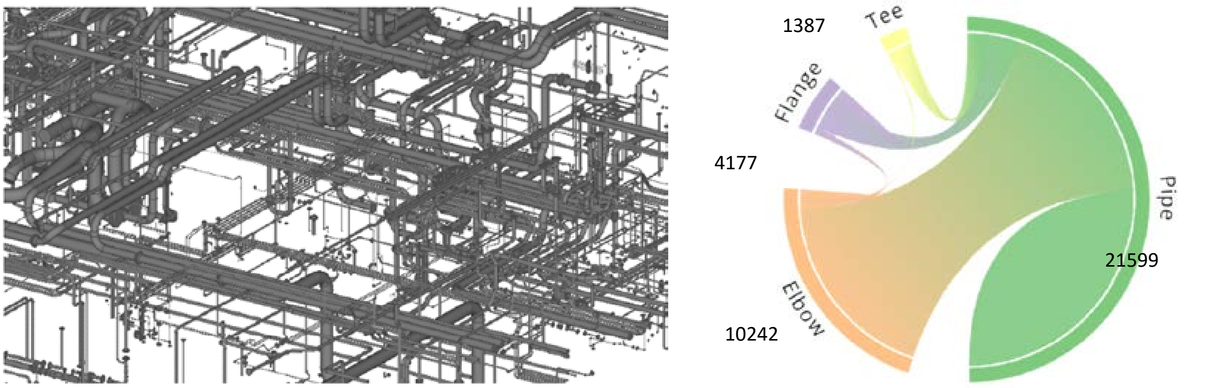

Figure 2. A subsection of the input dataset (left) and element relationship frequencies (right).

Out of the proposed node feature representations, we test the bounding box and sampled subset of points strategies. The relative simplicity of these methods provides a starting point for assessing the feasibility of our solution. For the bounding box representation, we calculate the principal axis vector, centre-point, and dimensions of the minimum oriented bounding box. For the latter representation, we randomly sample 100, 500, and 1000 points for each element (Figure 3).

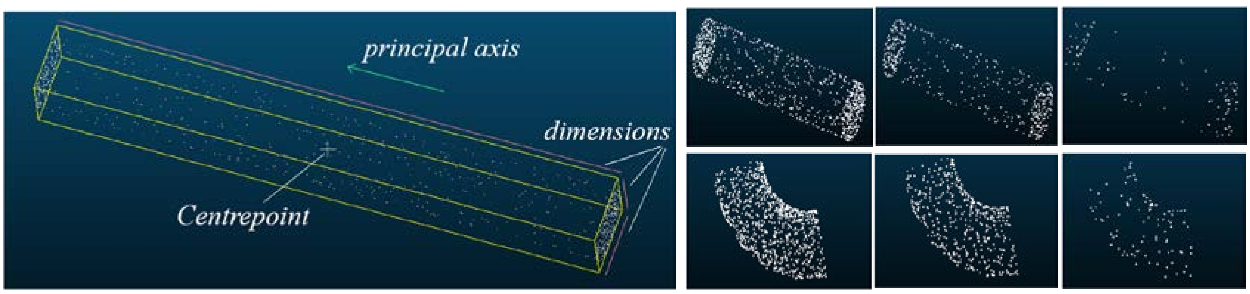

Figure 3. Node features derived from bounding box (left) and Element points sampled at 1000, 500, and 100 points (right)

We experimentally determine that node features derived from bounding box geometry provide best results. Our graph representation consists of a graph whose nodes represent individual elements, and whose edges denote topological relationships between the elements. Each node is represented by a feature vector consisting of the above bounding box parameters. Specifically, the principal axis is represented by a 3D unit vector, and centre point and dimensions are also represented by 3D vectors. The class label of the element is appended to the feature vector using a one-hot encoding.

The link prediction GNN and graph dataset were implemented using PyTorch and Deep Graph Library. The training/validation set consisted of around 20,000 elements and 17,000 topological relationships. 10% of this set was reserved for validation. Furthermore, a separate, disjoint section of the design file dataset was used as a test-set, ensuring that the trained model scales to unseen graphs. The test-set comprised of around 17,000 elements and 15,000 relationships. For training, we generate a positive graph containing all edges in the training set, and a negative graph containing the inverse of those edges. As each element could potentially be connected to every other element, the negative graph contains an exponentially large number of edges. Therefore, we sample a subset of edges to create a balanced training set. The sampling is performed dynamically during training to include all potential negative edges. Furthermore, we restrict our search to potential edges between elements within a pre-defined range and generate pseudo edges based on physical proximity between elements.

Our proposed GNN is based on the GraphSAGE architecture and contains 2 GraphSAGE layers for node feature aggregation, as well as a 2-layer Multi-Layer Perceptron (MLP) for edge feature computation. The node features act as input for the 1st layer of the GNN. In a single layer, features of each nodes' neighbours are aggregated using mean aggregation, and combined with its previous features and a trainable weight vector. Next, edge features are computed to calculate probability of a link. We evaluate two prominent edge feature predictors, namely dot product and MLP, and determine that an MLP with two layers and a Rectified Linear Unit (ReLU) activation function yields best results. The model is trained using Binary Cross Entropy loss.

5. RESULTS AND DISCUSSION

Performance comparisons of hyperparameters are given in table 2. Training losses failed to converge when training with sampled points as node features. Thus, all results listed in the table utilize bounding box parameters and element class label as node features. All models were trained for 500 epochs, with Adam optimizer and a learning rate of 0.01.

Overall, the system achieves a recall of 0.88, precision of 0.51 and F1 score of 0.64 on the test-set at 0.5 classification threshold. A breakdown of model performance on relationships between various element types is given in table 3. The drop in both precision and recall is primarily due to errors in pipe-pipe relationships, stemming from disjoint piping elements.

Table 2. Performance comparisons between various hyperparameters on validation set

	Precision	Recall	F1 score	AUC-ROC
Node representation update method (with MLP – 2 layers)				
1 SageGRAPH layer	0.967	0.771	0.858	0.879
2 SageGRAPH layers	0.980	0.738	0.842	0.967
3 SageGRAPH layers	0.976	0.737	0.840	0.924
Edge feature computation method (with SageGRAPH – 2 layers)				
Dot product	0.700	0.955	0.806	0.900
1 MLP layer	0.486	0.677	0.566	0.451
3 MLP layers	0.937	0.736	0.825	0.855

We also test model adaptability to real world data by testing on a manually annotated subset of the CLOI dataset containing flanges, elbows and pipes. Tees were excluded due to their low prevalence. The dataset contains around 600 relationships between around 1100 elements. We develop a new relationship annotation and visualisation tool based on LabelCloud, an open-source point cloud bounding box annotation tool (Sager et al., 2021) for this purpose. The model achieves a recall of 0.99, precision of 0.75 and F1 score of 0.85 on this dataset. The higher performance is a result of the dataset being less complex than the design dataset with less densely packed elements.

Table 3. Recall and precision by element type, in design file (top) and CLOI (bottom) testsets

Precision	Flange	Elbow	Tee	Pipe
Flange	0.74	0.94	0.88	0.93
Elbow		0.89	0.60	0.96
Tee			0.94	0.71
Pipe				0.24

Recall	Flange	Elbow	Tee	Pipe
Flange	1.0	0.98	1.0	0.97
Elbow		0.97	0.97	0.94
Tee			1.0	0.94
Pipe				0.76

Precision (CLOI)	Flange	Elbow	Pipe
Flange	0.25	0.93	0.85
Elbow		0.14	0.92
Pipe			0.70

Recall (CLOI)	Flange	Elbow	Pipe
Flange	1.0	1.0	1.0
Elbow		1.0	0.98
Pipe			1.0

Additionally, we visualise results by programmatically generating cylindrical elements at connection points to denote topographical relationships (Figure 4). Most false positives and false negatives occur on elements with smaller radii. In particular, the model predicts false edges on small parallel pipes. Parallel pipes connected via two elbows are another cause of false positives. The model is also more likely to miss relationships in densely packed regions. Notably, errors are more prevalent among smaller connecting elements such as tees. This may be attributed to shortcomings of the node feature representation. Unlike pipes, smaller elements such as tees or elements do not have an unambiguous principal axis. Therefore, a bounding box representation may be inadequate to represent their geometry. Switching to more descriptive features such as element parameters may prove to be a valuable avenue for future work. Visual analysis of CLOI dataset results (figure 5) demonstrates that errors are primarily false positives mainly caused by noisy point clusters. This is explained by the high sensitivity of the bounding box representation to noisy points.

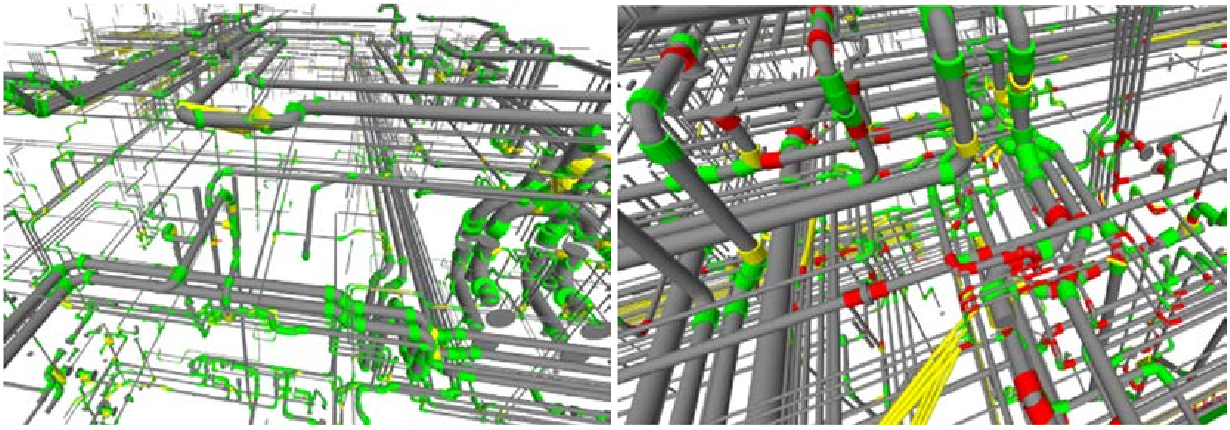

Figure 4. Model predictions (left), and failure cases (right) on design file testset and predictions on CLOI dataset (bottom) (True positive=Green, False positive=Yellow, False negative=Red)

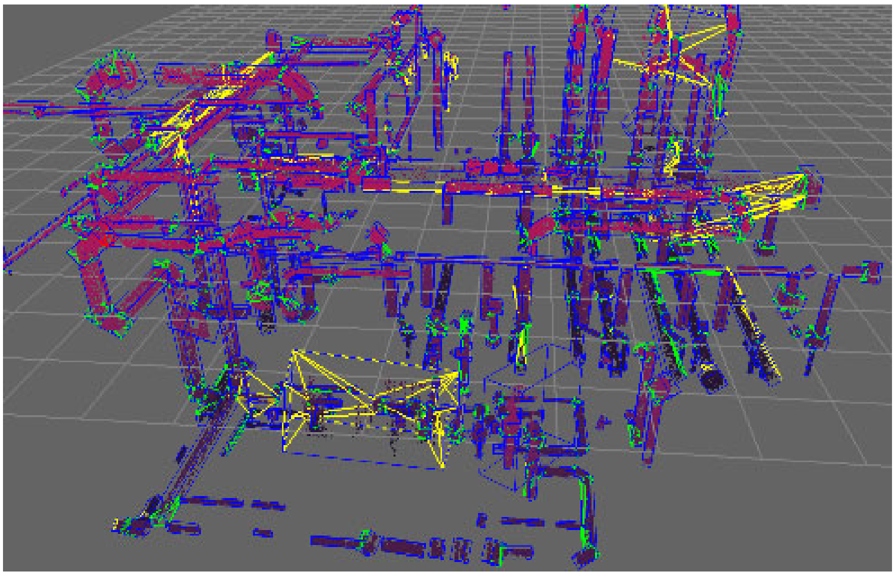

Figure 5. predictions on CLOI dataset. Edges are denoted by lines between edges of element bounding boxes (True positive=Green, False positive=Yellow, False negative=Red)

6. CONCLUSION

We propose a novel method for automatically identifying topological relationships between elements within industrial facility models using GNNs. Specifically, this research is the first to accomplish this task without a rule-based approach. While significant improvements are required to match the precision and recall of human annotators, our method demonstrates the feasibility of automated relationship inference, and can be used as guidance for annotators. Many failure cases are caused by limitations of the bounding box node representation. These include sensitivity to noisy points and inability to represent geometry of smaller elements accurately in densely packed areas. Thus, there is significant potential for future improvement by substituting a more advanced representations such as element parameters or a learned feature representation. Another limitation of the proposed method is low performance in the presence of occluded points, which are common in large scale indoor scans.

The method can also be extended to detection of aggregation relationships such as facility subsystems. Furthermore, the inferred relationship information may also be utilised as additional context to improve instance segmentation performance. Crucially, in contrast with previous hand-coded approaches in various domains, this paper presents an automated alternative to relationship inference, which is crucial to the semantic enrichment step of the scan-to-BIM process. It is thus suited for more complex scenarios, and is easily adaptable to other domains, making digital twinning more accessible to previously unexplored infrastructure domains.

ACKGNOWLEDGEMENTS

This research has received funding from the Engineering and Physical Sciences Research Council (EPSRC), AVEVA Group Plc. and British Petroleum Plc. Design file and scan datasets used in this research were provided by British Petroleum Plc. and AVEVA Group Plc.

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INDOOR TRAJECTORY RECONSTRUCTION USING BUILDING INFORMATION MODELING AND GRAPH NEURAL NETWORKS

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ABSTRACT: *Trajectory reconstruction of pedestrian is of paramount importance to understand crowd dynamics and human movement pattern, which will provide insights to improve building design, facility management and route planning. Camera-based tracking methods have been widely explored with the rapid development of deep learning techniques. When moving to indoor environment, many challenges occur, including occlusions, complex environments and limited camera placement and coverage. Therefore, we propose a novel indoor trajectory reconstruction method using building information modeling (BIM) and graph neural network (GNN). A spatial graph representation is proposed for indoor environment to capture the spatial relationships of indoor areas and monitoring points. Closed circuit television (CCTV) system is integrated with BIM model through camera registration. Pedestrian simulation is conducted based on the BIM model to simulate the pedestrian movement in the considered indoor environment. The simulation results are embedded into the spatial graph for training of GNN. The indoor trajectory reconstruction is implemented as GNN conducts edge classification on the spatial graph.*

KEYWORDS: *Indoor trajectory reconstruction; Graph neural network; Building information modeling; Camera-based tracking; Spatial graph; Pedestrian simulation*

1. INTRODUCTION

Indoor trajectory reconstruction refers to the process of estimating the path or trajectory followed by a moving object or person within an indoor environment. This can be useful in various applications, such as indoor navigation, activity recognition, or monitoring systems. There are different approaches to indoor trajectory reconstruction, including sensor-based methods and computer vision (CV) techniques. Sensor-based methods rely on sensors, such as accelerometers, gyroscopes, magnetometers, or depth sensors, to track the movement of an object or person. The sensor data is processed using techniques like sensor fusion or Kalman filtering to estimate the trajectory (Patron-Perez et al. 2015). This approach is commonly used in devices like smartphones or wearable devices. Wi-Fi or Bluetooth signals can also be used to estimate the location of a device within an indoor environment (Traunmueller et al. 2018). By measuring the signal strength from different access points or beacons, it is possible to determine the approximate position of the device. Trajectory reconstruction can be achieved by tracking the device's movements over time using signal strength variations. However, as people pay more attention to privacy, these methods have become more controversial and inconvenient, since it requires pedestrians to actively upload signals. CV techniques can be employed to reconstruct trajectories using visual information captured by cameras or depth sensors (Wong et al. 2022). These methods may involve object detection, tracking, and motion estimation algorithms. For example, by tracking the position of a person in multiple frames of a video, it is possible to reconstruct their trajectory within the indoor environment. In this regard, CV techniques are more acceptable for public as it required less information exposure.

Person re-identification (ReID) is a CV task that involves identifying and tracking individuals across different cameras or video frames (Zheng et al. 2015). The goal of ReID is to match a person's identity across non-overlapping camera views or at different points in time within a video sequence. In scenarios such as closed circuit television (CCTV) systems, where multiple cameras are installed in an area, ReID can help track individuals as they move between camera views. It is particularly useful in crowded or complex environments where traditional tracking methods may fail due to occlusion or changes in appearance. ReID applies deep learning techniques such as convolutional neural networks (CNNs) to extract discriminative features from the person's appearance (Cheng et al. 2016), which are further compared among different individuals to match the same person's features while differentiating them from others. However, ReID performs differently indoors and outdoors, as they differ significantly in terms of lighting conditions, camera placement, and occlusion. Indoor environments often have controlled lighting and less occlusion of pedestrian, which can result in more consistent appearance of individuals, thereby ReID algorithms usually could achieve better performance. However, indoor cameras are often installed at fixed positions with controlled angles and have narrow fields of views and limited camera coverage due to the narrow space of indoor environment and occlusion of building elements. It is not realistic to install cameras to

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Mingkai Li, Peter Kok-Yiu Wong, Cong Huang, Jack Chin-Pang Cheng, *Indoor Trajectory Reconstruction Using Building Information Modeling and Graph Neural Networks,* pp. 895-906, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.89

cover all indoor space as it requires large investment and maintenance cost in CCTV system. Hence, other techniques are required to enable indoor trajectory reconstruction.

Building information modeling (BIM) is a powerful tool for building management and provides a common data environment to connect different platforms to support various applications (Song et al. 2022; Cheng et al. 2022). Integration of BIM and CV techniques has emerged as a hot topic in recent years and unlocks a lot of applications. For example, construction activities can be recognized and analyzed by CV algorithms, and the relevant information can be extracted and intergraded into BIM model to improve the construction progress monitoring (Deng et al. 2020; Braun et al. 2020). Furthermore, information about the building components can also be intergraded in the digital representation of the BIM model for automatic detection and identification (Troncoso-Pastoriza, et al. 2018).

Graph neural network (GNN) is a type of deep learning model that is specifically designed to operate on unstructured data that can be represented as graphs (Zhou et al. 2020). The key idea behind GNNs is to propagate information across the nodes and edges of a graph, allowing each node to gather and update information from its neighbors. GNNs have shown promising results in various domains, including social network analysis, molecular chemistry, recommendation systems, and CV tasks involving graphs or structured data (Wu et al. 2020). In recent years, GNNs have been applied to the building design and management. Nauata et al. (2020) applied GNN to generate house layout following given relational architecture. Cheng et al. (2022) leveraged GNN to conduct crowd prediction in the building. In this regard, GNN is a potential technique to assist the indoor trajectory reconstruction as the building layout can be represented as a graph and can be further processed by GNNs.

This paper proposed an indoor trajectory reconstruction method using BIM and GNN. A spatial graph is proposed to depict the indoor environment. Pedestrian simulation is conducted using the agent-based model established based on BIM model to enrich the spatial graph. The CCTV system is integrated with BIM model by camera registration, so that the information generated by CV algorithms based on the cameras' videos can be related to specific location in the BIM model. With the information from CCTV system, the spatial graph is then processed by a GNN to reconstruct the indoor trajectory of pedestrian. Section 2 introduces the methodology in details, while Section 3 provides an example to illustrate the proposed method.

2. METHODOLOGY

The proposed framework of indoor trajectory reconstruction is shown in Fig. 1. The BIM model is first used to establish a spatial graph to describe the spatial relationship among the indoor spaces including corridors and rooms. To be specific, the floor plan of the Revit model is analyzed by a Dynamo algorithm to identify the entrances, exits, intersections and dead ends. These points would be nodes in the graph and corridors connecting these nodes would be edges. Besides, DWG file is exported from BIM model and imported into a pedestrian simulation software called AnyLogic. The movement of pedestrian inside the building is simulated. The required time for a person to move from one point to others is recorded and embedded into the graph as edge attribute. The CCTV layouts are linked to the BIM model by camera registration so that the identification of some person in the field of view of one camera can provide information of the location of the person in the building. ReID algorithm is adopted to identify a specific person across several cameras. The series of timestamps and positions of one person will be passed to the spatial graph and possessed by a graph neural network to identify the trajectory of this person.

2.1 Integration of BIM and CCTV System

Cameras have been widely used in buildings for safety and efficiency surveillance. Especially with the integration of artificial intelligence and building BIM, many intelligent applications have emerged. To unlock the potential of CCTV-BIM integration, the first step is to localize the cameras in the considered environment, based on which the event or person identified in cameras can be linked to specific position in the BIM model.

2.1.1 Camera Registration with BIM

Camera registration, also known as camera pose estimation, is the process of relating the camera coordinates to the real-world coordinates of objects or scenes. Some previous studies leverage conformity of geometric primitives such as points, lines, and planes to determine the translation, rotation, and scale in reference to as-planned models or real world (Asadi et al. 2019). These methods usually require manual operation and rely on predefined viewpoint assumption including camera position and orientation (Lukins and Trucco 2007; Rebolj et al. 2008). Asadi et al. (2019) automated the registration process by performing an augmented monocular simultaneous localization and mapping and perspective detecting and matching between the image frames and their corresponding BIM views. Though automated methods are more efficient, manual approaches with low technical threshold are still common as the camera registration process is one-off for a scene as long as the cameras are fixed.

Fig. 2 shows an example of manual camera registration with BIM model. The position and rough orientation of the camera are provided, so that the objects such as doors and walls in the field of view (FOV) can be easily mapped to the building elements in the BIM model. Several characteristic points at the intersection line of wall and floor, such as corner points of walls, will be selected in the FOV, while their correspondences will be identified in the BIM model. The function for transforming the pixel coordinates in camera's FOV to global coordinates in the BIM model can further be established. For example, for the FOV in Fig.2, two characteristic points $C_1(C_1')$ and $C_2(C_2')$ are selected, for any point $C_p(x_p, y_p)$ in the FOV, its corresponding point C_p' can be determined by following equations.

$$x_p' = \frac{x_p - x_1}{x_2 - x_1}(x_2' - x_1') + x_1' \quad (1)$$

$$y_p' = \frac{y_p - y_1}{y_2 - y_1}(y_2' - y_1') + y_1' \quad (2)$$

The above equation can only be used for cameras with no distortion, otherwise some corrections are needed. When more than two characteristic points are identified, the coordinates can take the average of the calculation results of every pair of the points using the above equation. For a FOV where characteristic points could not be found, several markers with known global coordinates can be set on the floor, which can be easily identify in the camera's FOV to establish the transformation function.

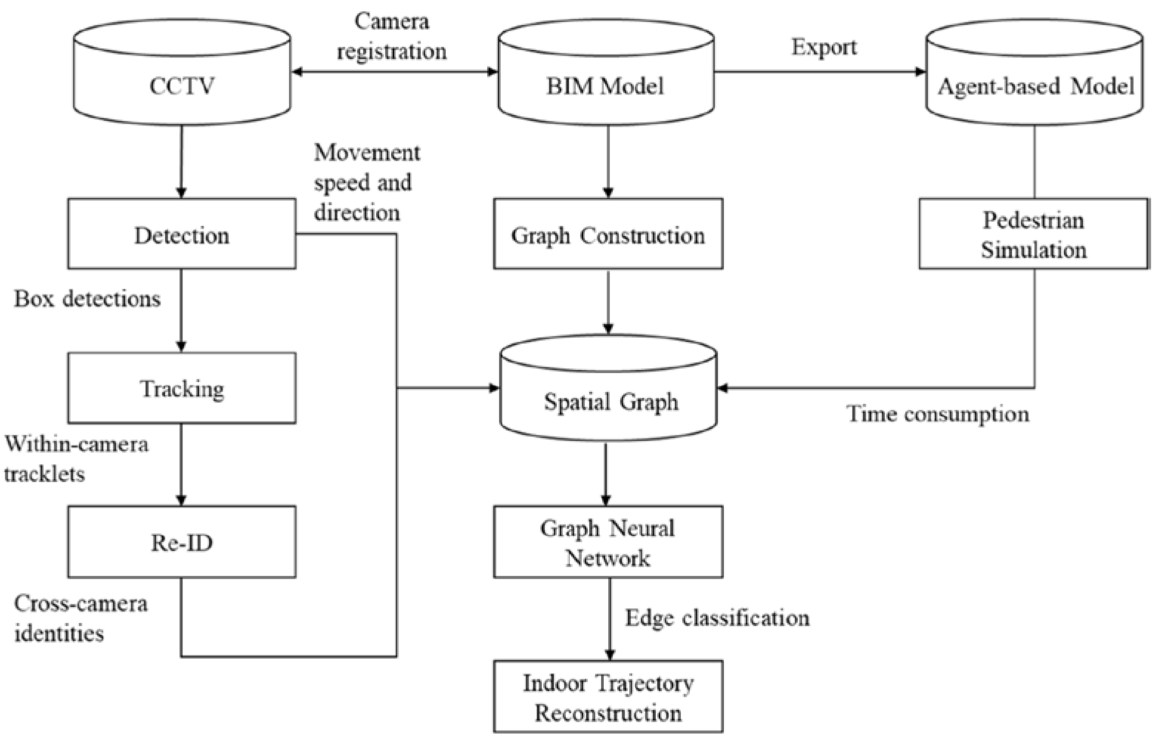


Fig. 1: Proposed framework of indoor trajectory reconstruction

Camera registration allows for accurate transformation between the real-world coordinates and the 2D coordinates in camera. It is crucial in multi-camera systems, where multiple cameras are used to capture a scene from different viewpoints. By accurately registering the cameras, it becomes possible to merge or fuse the information from different cameras and create a consistent and comprehensive representation of the scene. Overall, camera registration is a fundamental step in computer vision applications that involve cameras, enabling precise mapping between the real world and the image plane, and facilitating accurate measurements and analysis of the captured visual data.

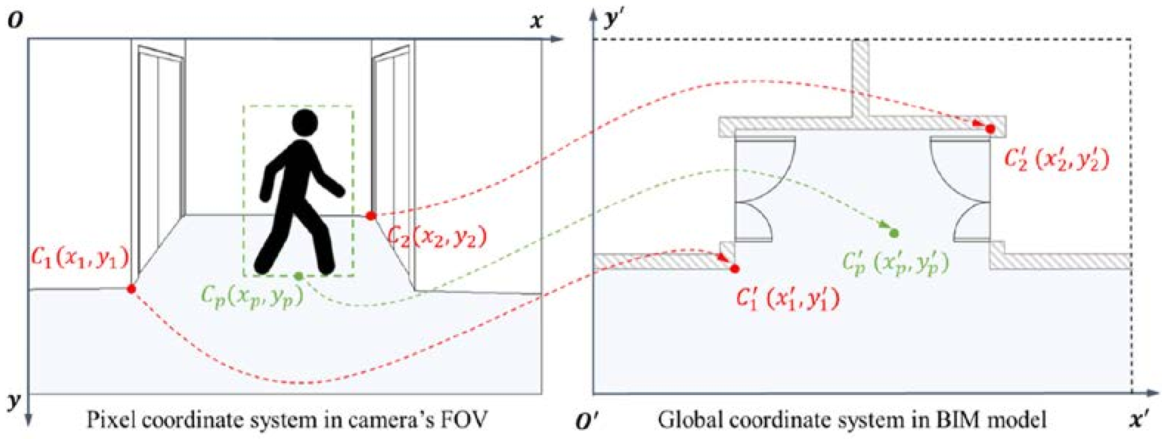


Fig. 2: Example of camera registration with BIM

2.1.2 Real-to-BIM

With camera registration, the information captured by CCTV system can be reflected into BIM. By adopting CV techniques, pedestrian can be detected with a bounding box. It is assumed that the midpoint of the bottom line of the bounding box can roughly represent the location of a person if the detection module in Section 2.3.1 reaches certain accuracy. Based on this, the movement direction of a person can be identified, which can be further matched with the directions of different branches of corridors to estimate the trajectory of the person. Besides, the speed of the person can be further calculated, as the movement distance of the person in real world can be achieved through transformation and the time consumed is also known.

As some cameras will be installed outside some rooms, the videos from cameras can be used to estimate whether a person has entered a room. Firstly, necessary information is extracted from BIM model using Dynamo, including door's dimension, door's location, and room's name. The location of a door is simplified as a segment AB on the 2D plane, while a person is abstracted as a point P. There are three cases based on the relative position of the line segment and the point, shown in Fig. 3. Based on this, we develop the algorithm to detect, when a person disappears from the video, the room he/she enters, or whether the person leaves, as shown in Fig. 4. For each point, we repeat such a process m times to collect the distances between this point and m line segments (doors), then regard the line segment that has the smallest distance as the final result. In other words, the closest door a person nears when he/she disappears is identified as the one the person enters.

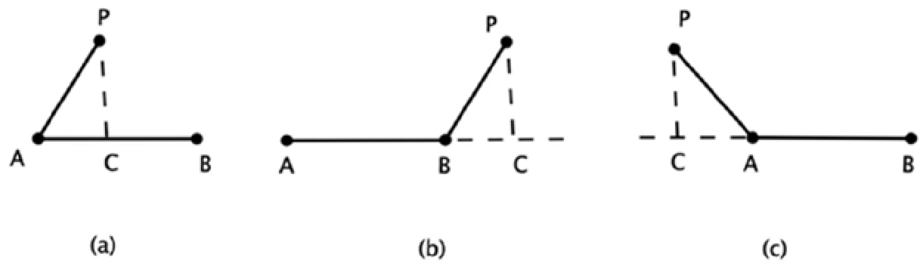


Fig. 3: Three cases for the shortest distance between a point and a line segment

2.2 Spatial Graph

Spatial graph is proposed to represent the indoor environment based on the BIM model. Besides, pedestrian simulation is conducted using agent-based model, which is derived from BIM model. The simulation results are then embedded in the spatial graph. With the information from CCTV system, the indoor trajectory can be reconstructed based on the spatial graph using GNN.

2.2.1 Graph Construction

Spatial graph is proposed by improving the medial axis transform (MAT) (Lee 2004) for indoor trajectory reconstruction. As shown in Fig. 5, MAT adds nodes at every turning point in the building, while spatial graph skips those nodes that are not fork, because the trajectory of pedestrian will not have multiple possibilities when passing through this kind of nodes. What these two methods have in common is that the edges in the both graphs represent sections of the corridor. Spatial graph includes several kinds of nodes: “entrance/exit” nodes (in green), “dead end” nodes (in dark green), “room” node (in orange), “fork” nodes (in red) and “camera” nodes (in blue). Dividing the nodes into different categories can depict the indoor environment more accurately and provide more information for GNN.

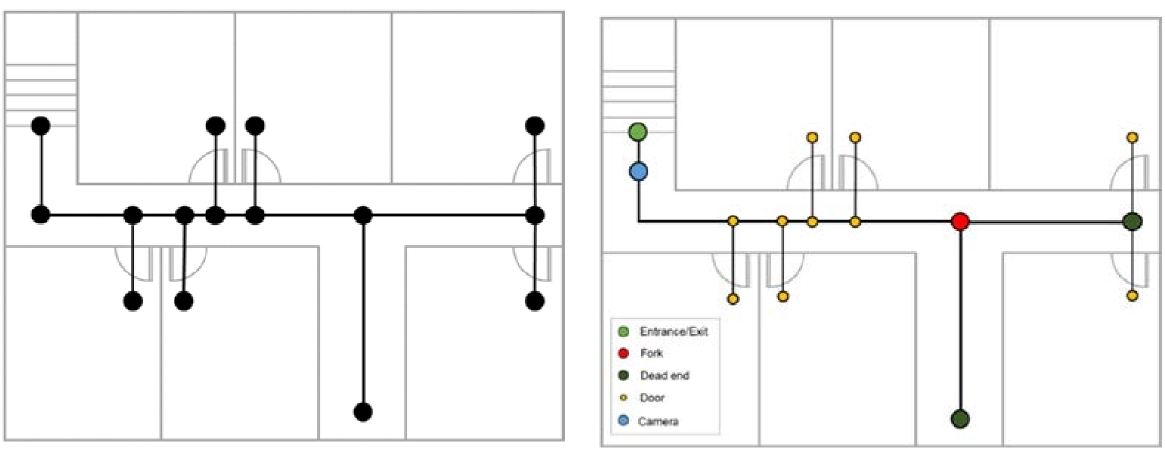
Algorithm 1: DETECT the room in which each person enters

Input: A person's coordinate P
A set of 2D vectors represent m doors $D = \{\overrightarrow{A_1B_1}, \overrightarrow{A_2B_2}, \dots, \overrightarrow{A_mB_m}\}$

$rid \leftarrow 0$
$dist \leftarrow \infty$
for $i \leftarrow 1$ *to* m **do**
  $C_i \leftarrow$ the projection point of P onto $\overrightarrow{A_iB_i}$
  $r \leftarrow (\overrightarrow{A_iP} \cdot \overrightarrow{A_iB_i}) \; / \; |\overrightarrow{A_iB_i}|^2$
  if $r \leq 0$ **then**
    $d \leftarrow |A_iP|$
  if $r \geq 1$ **then**
    $d \leftarrow |B_iP|$
  if $0 < r < 1$ **then**
    $d \leftarrow |C_iP|$
  if $d \leq dist$ **then**
    $rid \leftarrow j$
    $dist \leftarrow d$
$M_{rid} \leftarrow$ the midpoint of $A_{rid}B_{rid}$
if $|PM_{rid}| \geq k * |A_{rid}B_{rid}|$ **then**
  $r \leftarrow 0$
else
  $r \leftarrow rid$
return r

Output: The room in which the person enters $r \in [0, m]$

Fig. 4: Pseudo code to detect the room in which each person enters



(a) MAT (b) Spatial Graph

Fig. 5: Spatial graph compared with medial MAT (Lee, 2004)

2.2.2 Pedestrian Simulation

To achieve more information for indoor trajectory reconstruction, pedestrian simulation is conducted to analyze the behavior and the time required for a person to reach a specific position in the considered environment. We adopt agent-based modeling (ABM) for pedestrian simulation. ABM has been widely applied to simulate the real-world operation, particularly pedestrian movement, traffic network and manufacturing chain. The three main elements in ABM are agents, their attributes as well as behavioral rules (Cheng and Gan, 2013). Each agent is an autonomous component having its attributes defined by user-input parameters, such as its size and moving speed. Every agent also behaves according to a set of decision rules, for example, approaching multiple places in a specified sequence. With these characteristics, every agent in an environment persistently interacts with each other, in pursuit of specific objectives.

There have been extensive case studies that were able to simulate human behaviors in various scenario. Said et al. (2012) modeled how occupants in a high-rise building react in case of emergency and find the quickest evacuation route. On the other hand, Liu et al. (2014) demonstrated the functionality of ABM in simulating typical pedestrian flow phenomenon, such as bidirectional flow in corridors and through bottlenecks. Their simulation result consisted of the flow rate, movement velocity and spatial density. Suggested by Seyfried et al. (2005), pedestrian flow is notably consistent with the fundamental traffic theory. This inspired us to analyze the speed-density-flow relationship for pedestrian movement, by adopting traffic flow theories.

One typical ABM engine is AnyLogic, which possesses excellent user-friendliness by allowing graphical drag-drop control and advanced Java codes. Moreover, it supports realistic visualization by either component markup or importing geometric models from external application. In this paper, the BIM model is imported to AnyLogic using DWG file as intermedia. Then the walls of the building can be generated automatically. By setting the source and target of pedestrian flow, the movement of pedestrian in the considered indoor environment can be simulated. Besides, we also added “line service” at the positions of fire doors (which are normally closed) to consider the time delay of passing the doors. The pedestrian queuing behavior and parameter setting are investigated by Kim. et al. (2013), which laid the foundation for establishing a robust framework for our project.

2.2.3 GNN-based Trajectory Reconstruction

With the pedestrian simulation based on ABM, the spatial graph can be further enriched with the time consumption information from one position to the other within the indoor environment. Each edge in the graph has two features: “time consumption” and “pass_or_not”. The former is a feature to indicate the time required for a person to reach a specific position from the other. The time is taken as the average value detected from the simulation. The latter is a binary-class feature showing whether a person has passed a specific path, which is represented by an edge. The movement direction mentioned in Section 2.1.2 is used to estimate the path that the person is most likely to travel through, which is achieved by matching the detected direction with the directions of different branched of corridors. Besides, each node will have 5 features: x-coordinate, y-coordinate, category, timestamp when a person is detected, and speed of detected person. “Category” refers to the categories of node according to Section 2.2.1. Speed of detected pedestrian relies on the camera registration and CV techniques to estimate the speed. For those nodes that no pedestrian pass, the value of this feature is set as 0. Base on this graph representation, the indoor trajectory reconstruction can be formulated as an edge classification task on graph, as shown in Fig. 6, aiming to divide all edges into those that pedestrians pass by and those that do not.

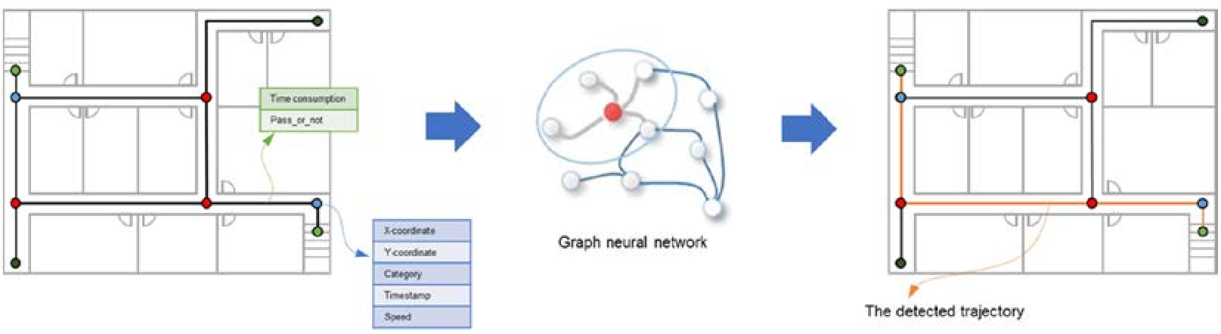


Fig. 6: Edge classification for indoor trajectory reconstruction

2.3 Multi-target Multi-Camera Tracking and Re-Identification

Given a query video, our method targets on detecting, tracking and identifying all people within this video, which is composed of three parts, a detecting module, a tracking module, and a ReID module. The whole framework is shown in Fig. 7.

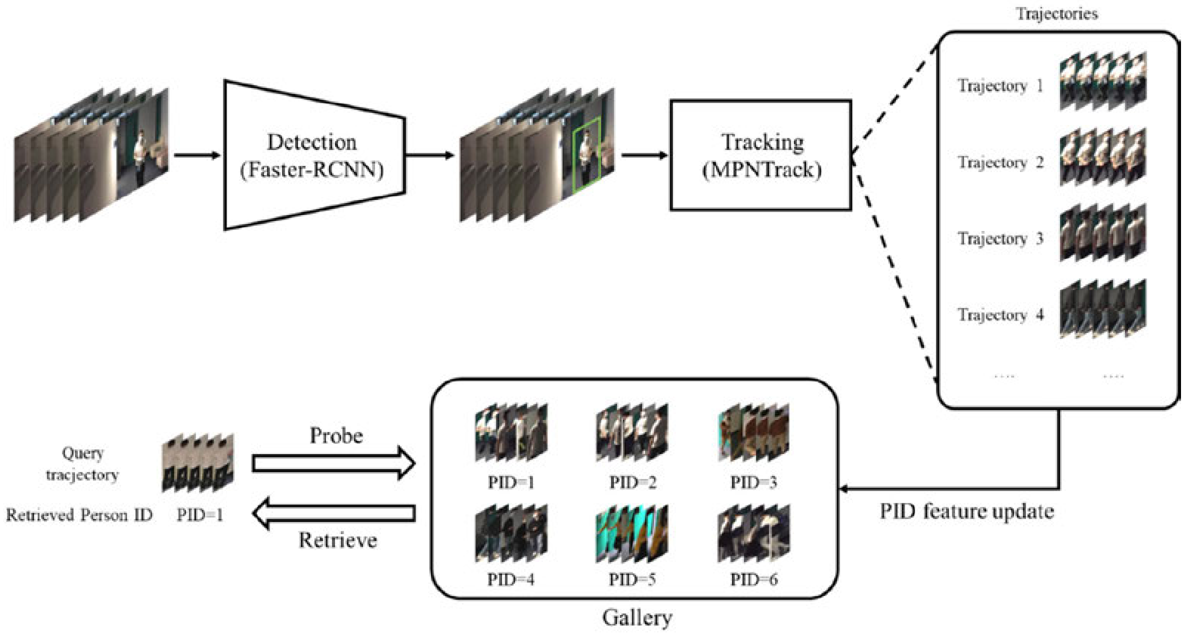


Fig. 7: The framework for multi-target multi-camera tracking and re-identification

2.3.1 Detection

For each frame in the query video, we first apply a Faster-RCNN (Ren et al. 2015) to detect all persons within this frame. In detail, given a frame, a CNN is applied to extract pixel-wise features, which are then sent to a region proposal network (RPN) to generate region-of-interest (RoI) which may contain a person. These regions are fed into another CNN classifier to determine whether they correspond to a person or not. Finally, a non-max-suppression (NMS) method is applied for redundancy removal. NMS first outputs the highest scoring box and then suppresses all overlapping boxes with that box, repeating this process until all boxes are processed.

2.3.2 Tracking

The tracking module works for aligning objects in later frames with those in previous frames. We use a GNN called MPNTrack (Braso and Leal-Taixe, 2020) to achieve this goal. To be specific, for positive predictions in each frame, we first apply a RoIAlign operation to extract their features. We then construct a graph. Features of positive predictions in each frame are treated as nodes, and all prediction pairs across frames form the edges within this graph. For each edge in this graph, we encode its feature as the deviation between the features of its two end nodes. These edge features are then passed through a multi-layer perceptron (MLP) for classification. If two end nodes of an edge correspond to the same person within two frames, we label it as one, otherwise zero. In this way, we associate predictions across frames, which predictions correspond to the same instance and which are not. Therefore, we derive appeared instances in the query video.

2.3.3 Re-ID

Finally, we deploy a Re-ID module to identify these instances. We first forge an instance gallery. Given the training videos, the detection and tracking module was first used to obtain different instances. We then randomly select n (n=10 in our experiments) instances for each person and store them in the instance gallery. We extract feature vector for each instance from the well-trained Re-ID model and use these feature vectors as the high-level semantic representations for persons. During testing, for different instances obtained from the query video, we treat them as probe, extract their feature vectors and retrieve their identifications stored in the instance gallery. Specifically, we compute the cosine distance between the queried feature vectors and all the stored feature vectors, and treat the person with the least feature distance as the output identification. The detailed structure is shown in Fig. 8.

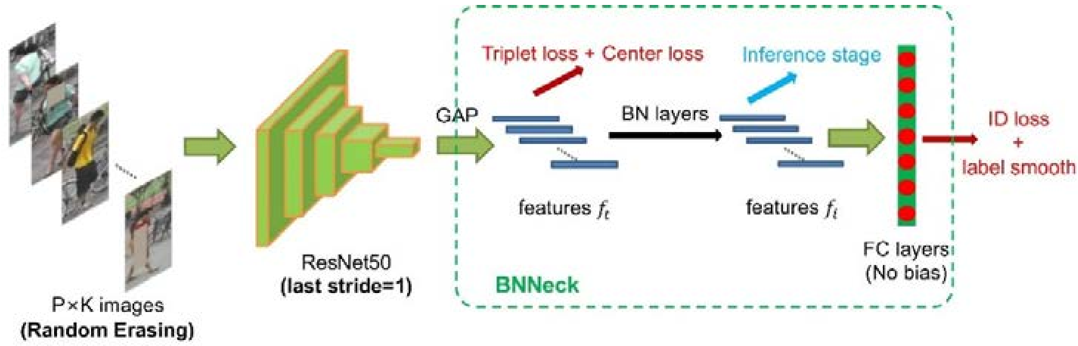
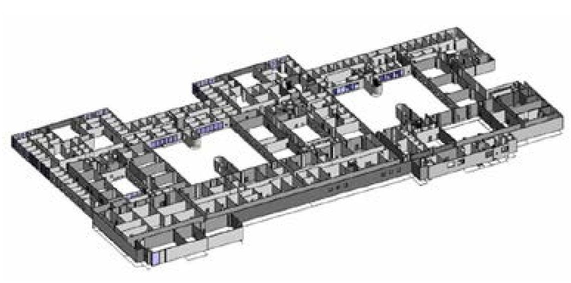


Fig. 8: The detailed structure of the Re-ID module (Luo et al. 2019)

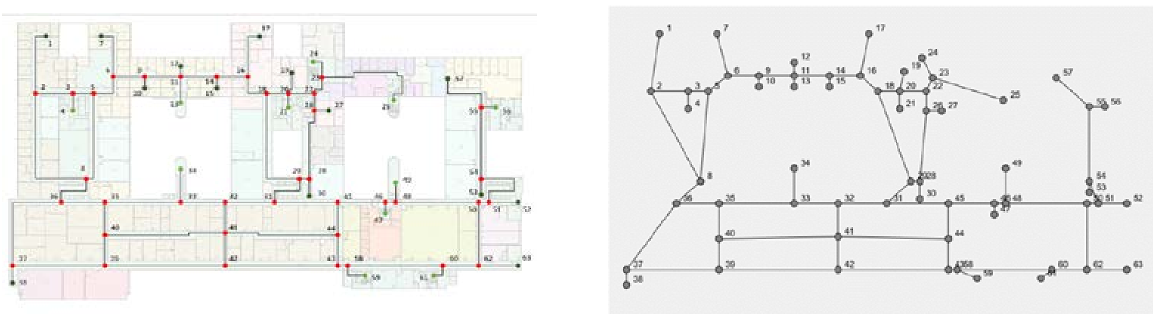
3. ILLUSTRATIVE EXAMPLE

We selected a part of the HKUST campus with more than 200 rooms to demonstrate the method proposed in this paper. Firstly, we developed a Dynamo program to derive the spatial graph based on the floor plan from the BIM model. Fig. 9 shows the process of graph construction. Then DWG file is exported to AnyLogic to support agent-based pedestrian simulation (as shown in Fig. 10) to enrich the spatial graph. Currently, the simulation model is established automatically based on the DWG file, though some manual adjustment is needed. The pedestrian flow logic is established manually, which could be automated with some further developed. We extracted the average time for pedestrian to reach a position from the other as the "time consumption" feature for the corresponding edge. Besides, by selecting different combinations of starting and end points, the movement of pedestrian in the building following designated paths can be simulated, the results can be further used to train the GNN.



(a) BIM model

(b) Floor plan



(c) Graph construction

(d) Spatial graph

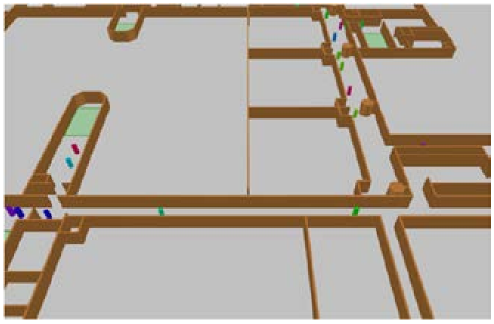
Fig. 9: Graph construction based on BIM model

The CCTV system is integrated with the BIM model through camera registration, so that the information captured by cameras can be linked to the specific location in the BIM model as well as the spatial graph. In our experiment, we conduct camera registration manually for 6 cameras using characteristic points and Equation (1) and (2). With the ReID techniques, the same person appears in different cameras' POV can be identified. The ReID model is pre-trained on a public benchmark -- DukeMTMC-reID (Ristani et al., 2016), and got an accuracy of 100% for the

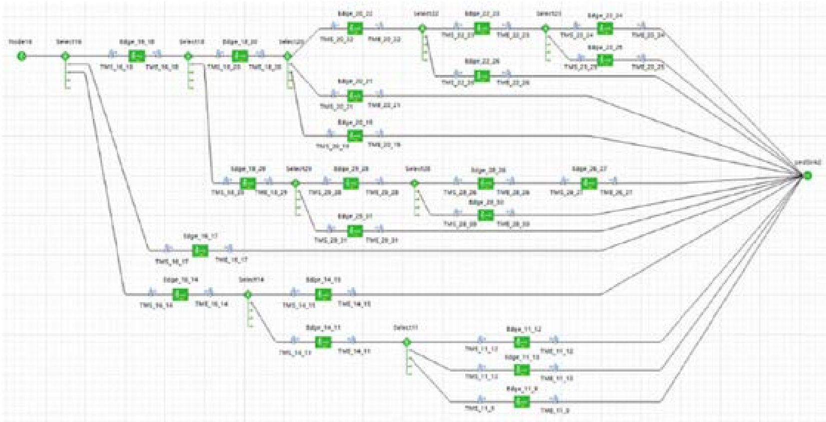
100 pedestrians we observed in the building. The high accuracy may result from the stable lighting condition and fewer pedestrian appearing in the FOV of each camera, compared to the outdoor environment.

Fig. 11 shows the feature maps and ReID process, while Fig. 12 provides an example of ReID results.

(a) AnyLogic model established based on BIM model



(b) 3D view of the pedestrian simulation



(c) Pedestrian flow logic

Fig. 10: Pedestrian simulation based on AnyLogic

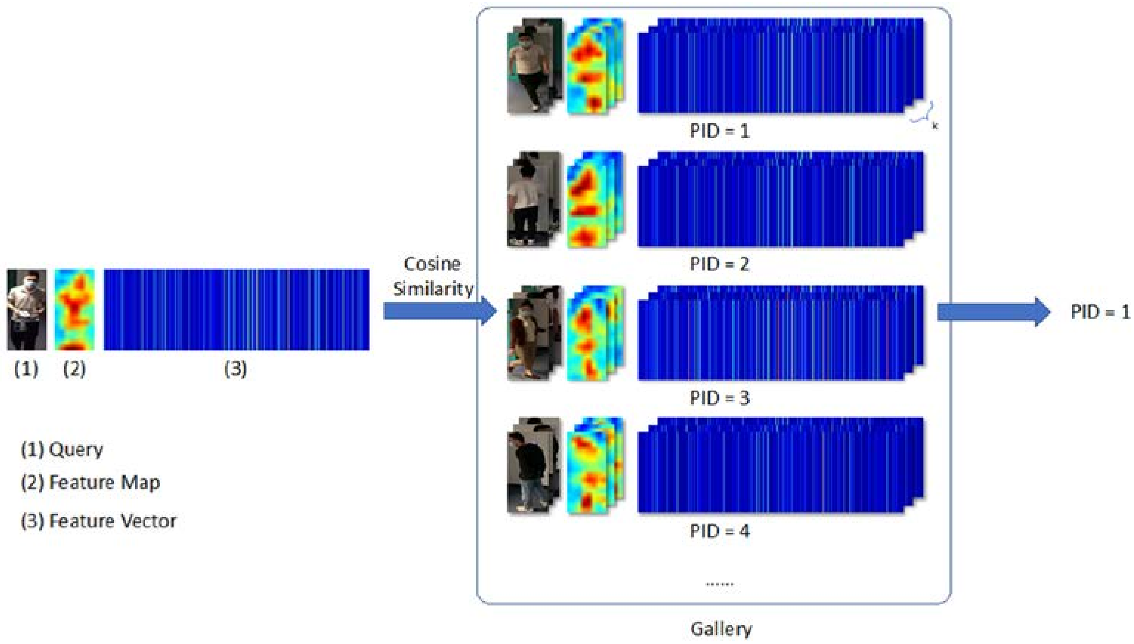
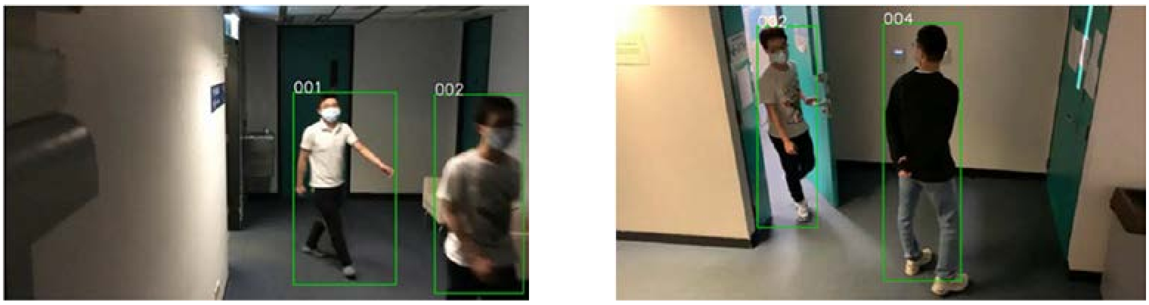


Fig. 11: Feature maps and Re-ID process



(a) Scene 1 (b) Scene 2

Fig. 12: Examples of the Re-ID results for the two cameras' videos

Information including ReID results as well as the direction and speed of the detected person were embedded into the graph and processed by GNN to make edge classification. The indoor trajectory can be reconstructed by classifying edges into 2 categories: those the person passed, and those did not. The GNN classification achieved 81.2% for the trajectories for the observed 100 pedestrians. We found that for some cases where pedestrians stopped during the process, GNN would produce some wrong classifications, since staying will affect the total time for a person to reach a specific location.

4. CONCLUSION AND DISCUSSION

This paper proposed an indoor trajectory reconstruction method integrating BIM and GNN. A spatial graph is proposed based on BIM to depict the connection of indoor spaces and integrate information captured by CCTV system. The CCTV system is related to the BIM model through camera registration. ABM-based pedestrian simulation is leveraged to simulate the movement of persons within the building, which provides more information to the spatial graph. Trajectory reconstruction is implemented using GNN, which works on spatial graph to aggregate information and classify edges. This study provides an automated approach to trace the pedestrian in the building, which could provide building managers with more insight in the indoor movement pattern and crowd distribution, and thereby could support a lot of smart applications such as indoor navigation, ambient-assisted facility management, precise product delivery, etc.

The proposed approach still has several limitations. For environments with a large number of rooms, the CCTV system usually cannot cover all the entrances of rooms due to limited number of cameras. In this scenario, for those rooms whose doors are not in the FOVs of cameras, we could not achieve the time of staying in the room for a detected person only using cameras, hence it may affect the GNN's performance on edge classification. Other techniques such as Internet of things could be explored to provide supplementary information for those positions that are not covered by cameras. Besides, optimization of camera layout can also be investigated to enlarge the coverage of camera and reduce blind areas. In addition, an automated camera registration method can also be included to improve the convenience of applying the proposed method.

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IMAGE SEGMENTATION APPLIED TO URBAN SURFACE AND AERIAL CONSTRAINTS ANALYSIS

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ABSTRACT: *The rapid progress of artificial intelligence (AI) has prompted the exploration of its potential applications in the construction industry, although at a slower rate. Since the starting point of a design is the analysis of the site's constraints, the purpose of the ongoing research is the application of artificial intelligence in risk assessment for site areas. The primary objective of this research project is to develop an interactive map that employs AI to identify potential surface and aerial interferences. This map aims to support planners, engineers, and architects during the site context analysis phase by providing real-time visualization of obstacles. The interactive map allows users to explore and analyze identified obstacles, enabling cluster markers and filtering of features. The results obtained from applying this approach in Milan, Italy, demonstrate its functionality and usability, highlighting the tool's ability to provide valuable information in both localized and citywide scenarios. Potential improvements such as size assessment and advanced marker generation are also being examined to enhance the management of surface and air interferences. The goal is to enhance the tool's functionality, accuracy, and planning efficiency in construction projects.*

KEYWORDS: *Image Segmentation, Risk Assessment, Construction Site, Clustering Techniques.*

1. INTRODUCTION

During the project execution phase, a multiplicity number of agents and situations may affect the organization and the functioning of a construction site in terms of time and costs of the project. Indeed, these elements of 'disorder' can cause activities outside the program with negative effects on the quality, work, and safety of workers. The presence of the yard can be also a potential operational problem as continuity, health, and safety must be ensured both within the yard and outside. Thus, both perspectives must therefore be studied bidirectionally, at the interface between the site and environment. In addition, potential problems that may arise in terms of the size and duration of the project must be carefully analyzed for the construction of the network and mobile infrastructure and mobile construction site.

The *operational criticalities* represent the construction process variables, not necessarily known a priori, which may cause difficulties or inability to perform planned works. The analysis of potential criticalities in construction projects helps to identify operational issues and anticipate additional costs or time needed to avoid surprises during the work. For this reason, developing a specific design analysis is fundamental to arriving at the execution phase with an informed attitude toward possible problem solving. Operational criticalities can be organized into five criticality classes related to different areas, adopted as:

- Surrounding situation: analysis of the several characteristics related to the construction site and its surrounding.
- Production: analysis of the relationship and the organization between functional-spatial design elements, technological-productive design elements, and the utilization of human/techniques/materials/resources which are crucial for efficient and cost-effective execution.
- Specific design elements: analysis of programming aspects of a project which may be left incomplete for a conscious choice caused by specific difficulties in obtaining useful data to improve the design.
- Health and safety of the site: evaluation of how preventive and protective equipment, organizational measures, and training can affect the time and cost.
- Contingencies: analysis of those situations outside the construction site which may occur without generating surprise.

The risk assessment is a crucial step in evaluating and comparing design options, as any identified issues can be addressed during both the design and execution phases. It is important to investigate criticalities beforehand to address and solve them during the execution phase. This helps to quantify any increased costs and construction times. Writing an operational criticality report can support the validation of the design and contribute to client and designer awareness of any unresolved criticalities. It is important to update the document regularly throughout each design phase. This ensures that any critical issues that are identified during the first phase are addressed, and

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Marco Lorenzo Trani, Federica Madaschi, *Image Segmentation Applied to Urban Surface and Aerial Constraints Analysis,* pp. 907-916, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.90

any new critical issues that arise in subsequent phases can be resolved with an improved level of detail. The question then arises of how to exploit existing models of artificial intelligence related to the analysis of images to create a support tool aimed at drafting the document on the identification and analysis of critical issues and its constant updating. Indeed, it may be applied during the different project phases: for example, when the site inspection has not yet been carried out, the analysis of images from Google Street View (GSV) of the area can help the designer to have a clearer idea of the context in which it will operate. Instead, if the analysis is carried out on the photographic survey of the site, also carried out at different times of the duration of the yard, it can help to keep the surrounding criticalities monitored. Some critical issues that may arise during the development of the work can be detected with greater precision and detail. Hence, this paper focuses on the operating criticalities relative to the surrounding situation of a yard. The project presented aims to create an interactive map through simple and easy-access implements. It wants to demonstrate how using an artificial intelligence model for image segmentation applied to input images from GSV, is possible to create an interactive map that accurately provides the position of possible criticalities. A tool of this type, although of simple structure, can be very useful to designers, architects, or engineers during an inspection. It can become a support from which to draw a list of elements to be evaluated once they arrive at the site, because obviously, it is not possible to avoid this activity.

2. LITERATURE REVIEW

The development of an interactive tool supported by artificial intelligence, that provides a constantly updated view of the critical issues due to the context can be a basis for the implementation of further improvements to better support designers and engineers. The dynamic nature of the map must be able to allow the continuous updating of the input data, ensuring a greater precision than the static maps provided by the geographic information systems (GIS) (D. Farkas et al., 2016) which may contain inaccuracies or outdated information, regarding the positioning of services and sub-services.

The contextualization of the intervention plays a crucial role in construction projects. It involves a thorough study of the site, its surroundings, and the internal factors that directly impact the time, cost, and feasibility of individual operations. In today's construction industry, where companies often face significant pressure to meet strict time and budget targets, insufficient evaluation and consideration of surrounding constraints can result in an unsafe and accident-prone workplace (E. Rahnemay et al., 2017). Addressing these challenges, the integration of artificial intelligence with Building Information Modeling (BIM) has gained prominence in recent years (Y. Pan et al., 2022). This integration offers the potential to handle the vast amounts of complex and uncertain data present in construction projects more reliably and efficiently.

2.1 The Dense Prediction Transformers Model

Fully convolutional networks are the prototypical architecture for dense prediction (Long et al., n.d.; Sermanet et al., 2013). Dense prediction, a foundational challenge in computer vision, entails leveraging input images to generate intricate output structures such as semantic segmentation, depth estimation, and object detection through learning (Liu, 2021).

Convolutions are linear operators with a restricted receptive field, which requires sequential stacking in deep architectures to attain a comprehensive context and substantial representational capacity due to the limited receptive field and expressivity of individual convolutions. The image segmentation model used for the development of the tool in this paper was developed by Ranftl et al., who introduced Dense Prediction Transformer (DPT). DPT is an architecture for dense prediction tasks that adopts an encoder-decoder design, where the encoder utilizes a transformer as its fundamental computational building block. Notably, the authors employed the vision transformer (ViT) proposed by Dosovitskiy et al..

Thus, this model introduces a distinct architecture that replaces the conventional convolutional neural network. The main advantage of the vision transformer lies in its ability to generate a consistent and high-resolution global receptive field at each stage. Unlike the traditional convolutional approach, which examines individual windows gradually, transformers possess a unique mathematical architecture that establishes relationships between each neuron or zone in an image and each other. As a result, transformers show a relational nature, considering the entire image simultaneously in each position. This attribute facilitates the generation of predictions that are more refined and globally consistent than fully convolutional networks.

3. SURROUNDING SITUATIONS

The surrounding situations class is crucial as thoroughly examines the variety of factors that are closely related to the construction site and its surroundings. These factors can have a significant impact on work time and cost, influence the construction site's layout, and how materials are stored, handled, and manufactured (Marco Lorenzo Trani, 2012).

Speaking of yard contextualization, are numerous categories of operating criticalities to analyze and report in the analysis of criticalities document. Indeed, within it, problems deriving from site location in an urban fabric, hydrogeological characteristics of the site, subsurface constraints and due to the sub-services, aerial and surface constraints, also analysis of the environmental impact of the yard and the interference it may have with other nearby activities, are reported. Therefore, based on the categories of objects that the DPT model can recognize, seven elements have been identified on which to base the realization of the model (buildings, trees, plants, signboards, streetlights, skyscrapers, and poles), representative of certain categories just mentioned, going to focus the attention on localization in the territorial context, surface features, surface features, aerial restriction, and interferences with other activities.

The first mentioned controls the general access conditions to the construction site which may represent a potential operation criticality. For example, where the primary road is restricted, uneven, or overcrowded, it may be imperative to carry out extra measures to enhance the current road infrastructure or build new infrastructure to satisfy requirements. In case of temporary unavailability of the usual routes, the absence of alternative routes can further think hard about the planning of certain supplies to reduce the risk of a failed delivery or of lack of construction site-free spaces. The presence of road constraints for example represents a potential operational criticality in relation to the need to acquire dispensations or permissions from the public body. If the usual routes are temporarily unavailable and there is no alternative, it's important to carefully consider the planning of supplies to minimize the risk of failed deliveries or lack of space at a construction site. Road constraints, such as the need for dispensations or permissions from public bodies, can also create operational challenges. In the project developed this translates into the realization of the street network for the area under examination based on driveways, to provide an analysis of the critical issues concerning the main roads.

The technological-architectural, urban, and naturalistic preexistences represent a source of potential criticality, for example, the presence of a cantilever roof that, because of its height, doesn't allow the site access. As part of the project, the surface features were considered in the analyzed area by identifying the nearby buildings. Evaluation of neighboring buildings, in addition to influencing the height development of the yard, may also determine the choice of specific workings to avoid damage to elements not belonging to the site.

The presence of plants, trees, or poles in the area can pose a significant challenge to the safe and efficient operation of construction activities. This includes both aerial and mechanized handling, as well as the installation of temporary structures like scaffolds. Therefore, the aerial restriction analysis is important to ensure that these obstructions do not hinder the proper functioning of the construction site and that cranes can rotate freely at night without interfering with nearby buildings.

Lastly, the construction site's proximity to other productive activities can be a potential operational issue since the continuity, healthiness, and safety of both subjects must be ensured. If the site involves public services, the protection of service users is also considered in the critical analysis. Both perspectives need to be investigated in the interface between the construction site and the environment. The healthiness or hazardous elements generated from the environment to the site must be evaluated concerning the anthropic use of the environmental system. Additionally, potential issues that may arise in terms of the project's size and duration must be carefully analyzed for the construction of network infrastructure and mobile yards.

4. THE PROJECT

The purpose of the presented project is to identify potential surface and aerial interferences that may affect the area where a construction or civil yard is expected to open. To achieve this, an interactive map was created using the Python library "*folium*" to pinpoint the exact location of these obstacles. Python code was used to generate a street network for an interactive map using Google's OpenStreetMap. Users could choose to create the network for an entire city or a portion by entering coordinates or neighborhood names. The Lambrate and Città Studi neighborhoods in Milan were analyzed for this paper project. By incorporating the street network into the code, geographic coordinates were established that allowed downloading images from Google Street View. To ensure that ample data was gathered for identifying constraints, the network points were settled to be downloaded at a consistent distance of 25 meters.

In Figure 1, the road network generated is shown. Figure 2, with the orange points, shows the 2625 points identified for the analysis: each of them is characterized by an ID which is associated with the longitude and latitude of the position where it is located. After which, the corresponding images through GSV were downloaded. It’s important to note that there isn't a direct correspondence between points and images, as GSV provides multiple frames from different angles. This feature worked to benefit the project, as it allowed to detect possible interferences with greater accuracy.

Fig. 1: Milan neighborhoods street network

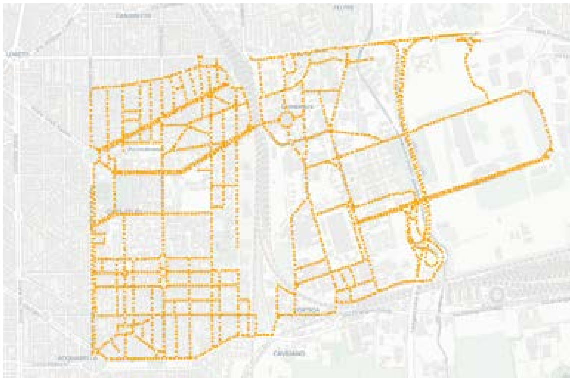

Fig. 2: 2625 street network points arrangement

Once the images were downloaded the DPT Model was utilized to analyze them. Rather than using object detection, image segmentation was chosen in the tool for obstacle identification due to its approach. It processes of classifying each pixel of the image into a class or label that identifies the occupied area of the object that can be recognized by the algorithm. This model proved to be highly effective in recognizing a wide range of possible obstacles, even in urban environments with numerous overlapping elements, limited image quality, or small obstacle sizes. In Figure three, how the process works it shown. The first row displays the input data in the form of images from GSV. Meanwhile, the second row showcases the model's image segmentation results. By utilizing pixel classification based on the labels integrated into the model, the reconverted objects like machines, poles, and bicycles can be identified in the images.

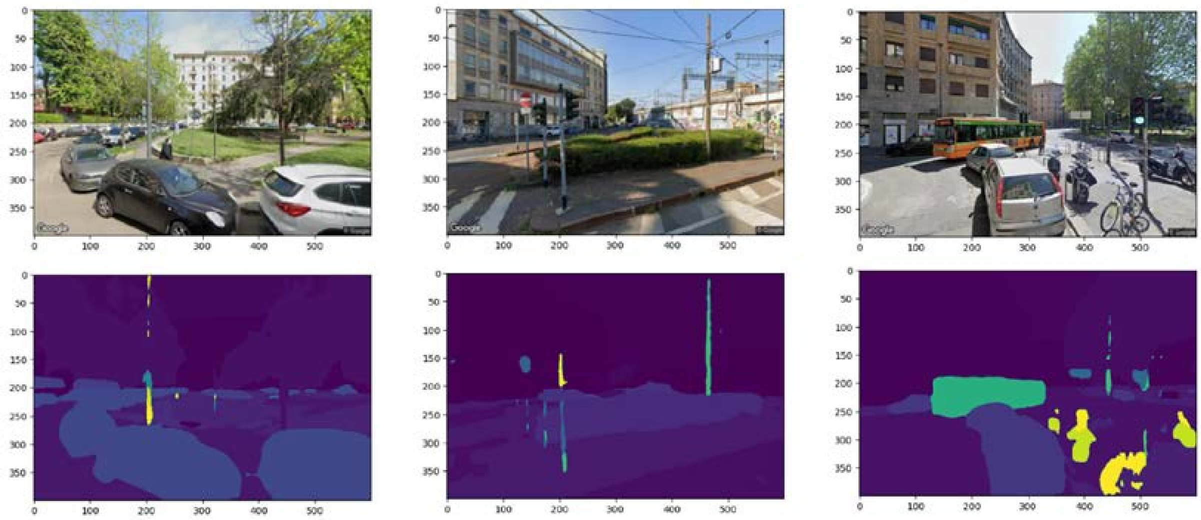

Fig. 3: Example of images segmented by the model

The model was trained to recognize over a hundred objects and use a filtering command to store outcomes for the most relevant constraint elements, including buildings, trees, plants, signboards, streetlights, skyscrapers, and poles a new CSV file with results was created.

After conducting Image Segmentation, the focus shifted toward visualizing the identified constraints. Upon counting the objects, it was observed that there were over 10,000 potential constraints that were recognized. The table below categorizes and counts these constraints.

Table 1: Number of elements recognized from 10500 images analyzed by Image Segmentation Model

Element	Building.	Tree	Plant	Signboard	Streetlight	Skyscraper	Pole	Total
Total	1882	1868	1563	1749	1655	4	1499	10220

Using the Folium library, constraint indicators have been configured with precise geographical coordinates from the road network generated previously: the code iterates each element of the CSV file containing the data related to the project. For each obstacle a marker has been generated that has been assigned a color based on a color dictionary for quick and easy identification. Included is the option to select markers, which displays a popup with specific information such as object name, image segmentation result, latitude and longitude coordinates, and reference image. Additionally, is possible to have multiple markers linked to the same image input. This is due to the fact that the image segmentation was done on the same input, resulting in different outcomes for the two objects. The reason for this is that during analysis, the model searches for all the elements it was trained for, as shown in Figure 3. Therefore, having the same references within the popup is not an indication of an error.

Let's examine the output tools in detail, focusing on their key features and assessing the advantages and disadvantages of the chosen representatives. The main difference between them lies in the type of marker used. The first tool employs *CircleMarkers* to indicate obstacles, while the second uses *ClusterMarker*.

To identify the position of obstacles in the studied area, the first tool created uses CircleMarkers for each element. These markers are color-coded based on the results obtained, allowing for a visual representation of the data. All the obstacles identified in Table 1 are displayed on the final map, thanks to the code implementation. Figure 4 depicts how the output appears to a user who has zoomed in on a specific area.

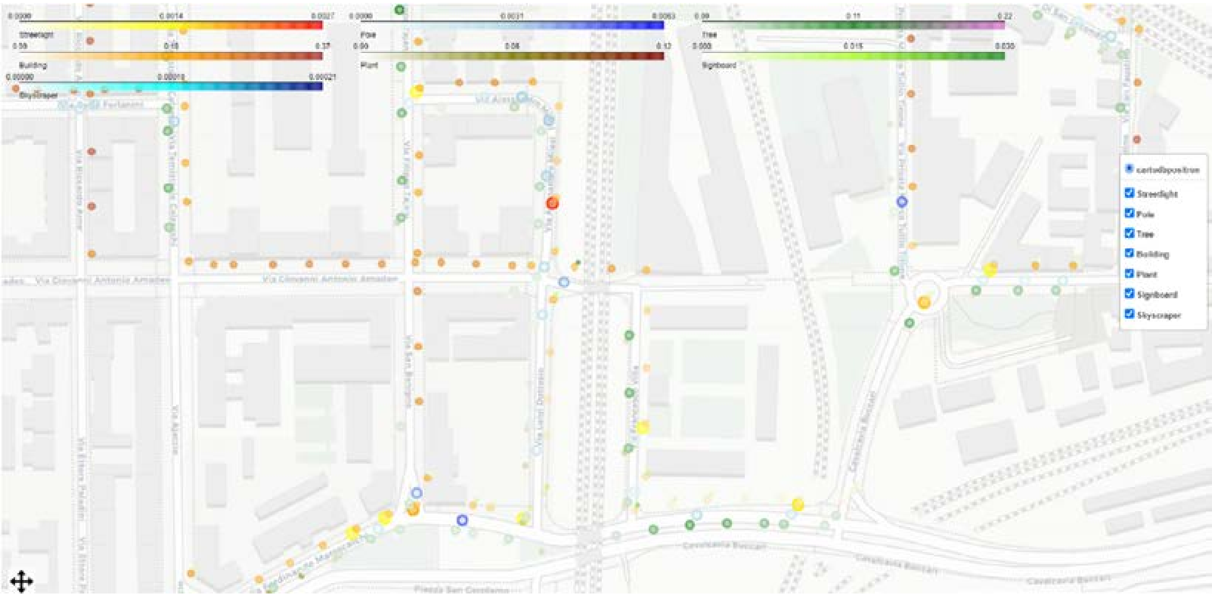

Fig. 4: *CircleMarkers* output map, zoom in is applied

To facilitate the reading of the position of markers, two solutions have been adopted. The first is general, inserted inside the code as a constraint for the positioning of the various indicators according to the reference category. In fact, an offset in the generation conditions within the map was made so that there was not a total overlap that prevented the display. Instead, the second solution concerns the possibility of managing the layers on which the markers have been inserted. Figure 4 shows that points with the same coordinates are slightly separated from each other. However, the exact location can be determined by selecting the marker of interest for the popup display. Different size radii were used to distinguish between the various markers, with their size gradually decreasing. To display or hide a marker, simply select it from the drop-down menu located on the left side of the map.

The second map proposed shows surface and air constraints via *ClusterMarker*. These markers are sued to clearly showcase clusters of data that are focused on a specific point while also indicating the number of elements in a micro zone. This is achieved by displaying circular markers that contain a numerical value within the area it covers.

By adjusting the map zoom, the markers can be enlarged or reduced. The groupings are distinguished by their color: green indicates a few markers, while red indicates a large number. In Figure 5 a visual representation of the second type of output is reported.

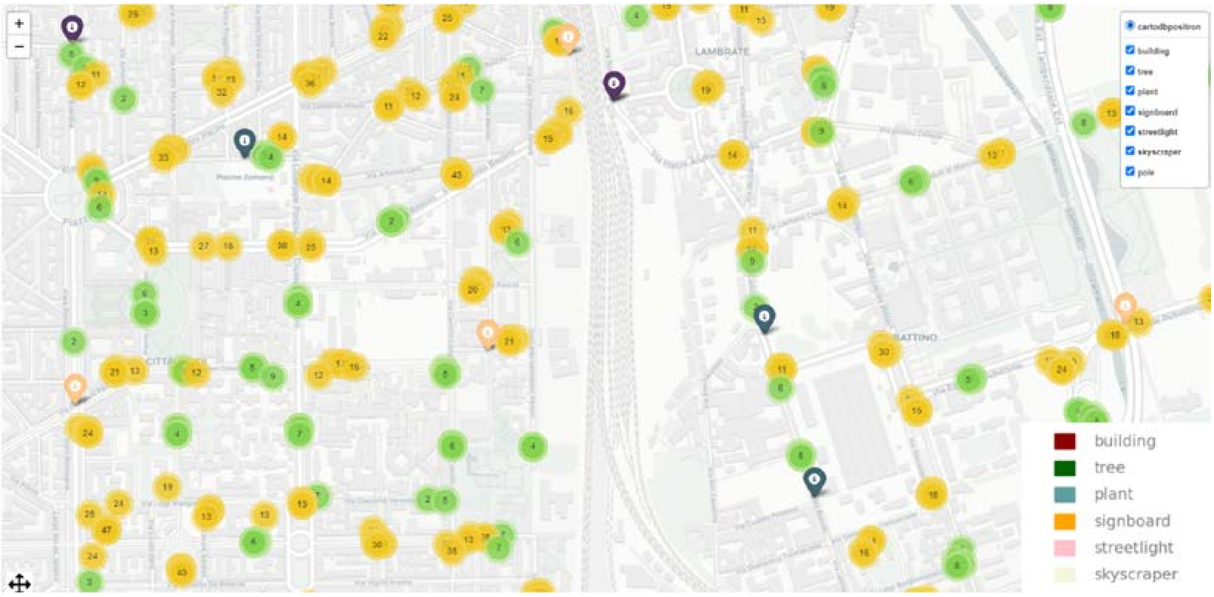

Fig. 5: *ClusterMarker* output map

This second output exhibits the same characteristics as the *CircleMarker version* but with distinct functions and interpretations. For instance, the filter option is always incorporated to allow for data selection, but instead of concealing layers, it directly hides the obstacle category. Moreover, the legend, located at the bottom right, no longer changes color scale based on outcomes, but rather on the classification of constraints, assigning a specific color to each. Figure 6 illustrates a zoom-in on the map to see more clearly the markers. However, when multiple groups appear at the same location, it can be challenging to get in an immediate overview of constraint positions. It is necessary to click on the specific interest group to view it. Moreover, there may be overlaps between groups associated with different categories and various *ClusterMarkers*, which can make the results less clear and immediate. Figure 6 demonstrates also how a popup appears when a marker is selected.

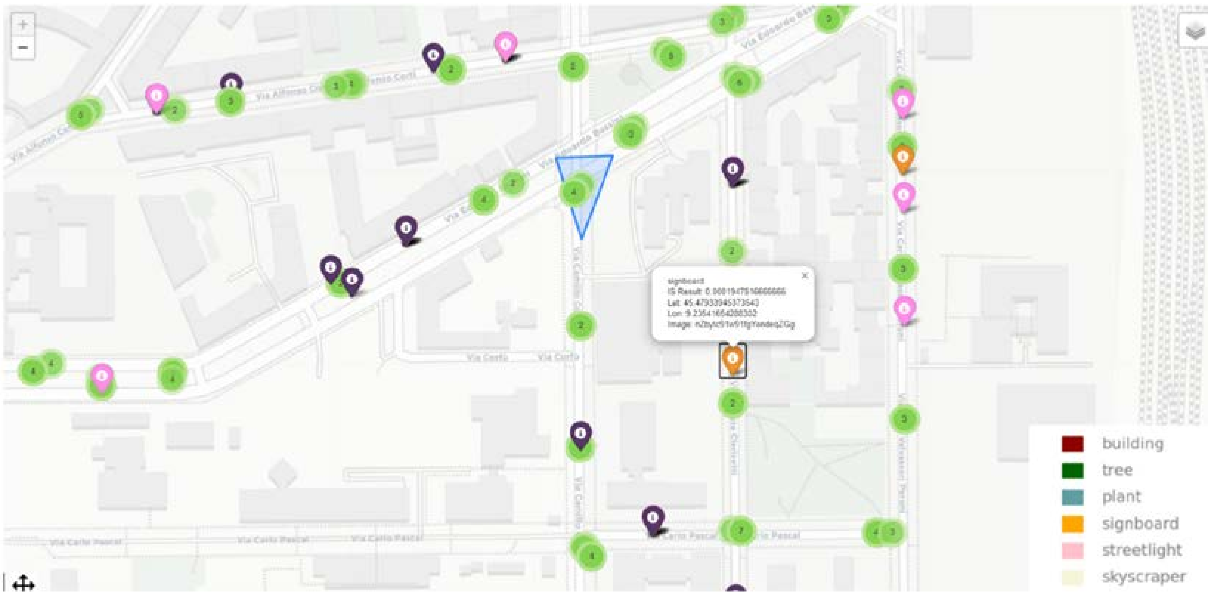

Fig. 6: *ClusterMarker* output map, zoom in and popup are applied

5. TOOLS APPLICATION AND VALIDATION

An application case was used to perform a thorough analysis of the tools' operation. In this case, the focus was on analyzing the criticality of the intervention that needs to be carried out at the junction of via Carlo Pascal and via Celeste Clericetti. Figure 6 depicts the map of the area before results from the analysis were included. The blue rectangle represents the intervention's position, while the red circle marks the specific area to be analyzed.

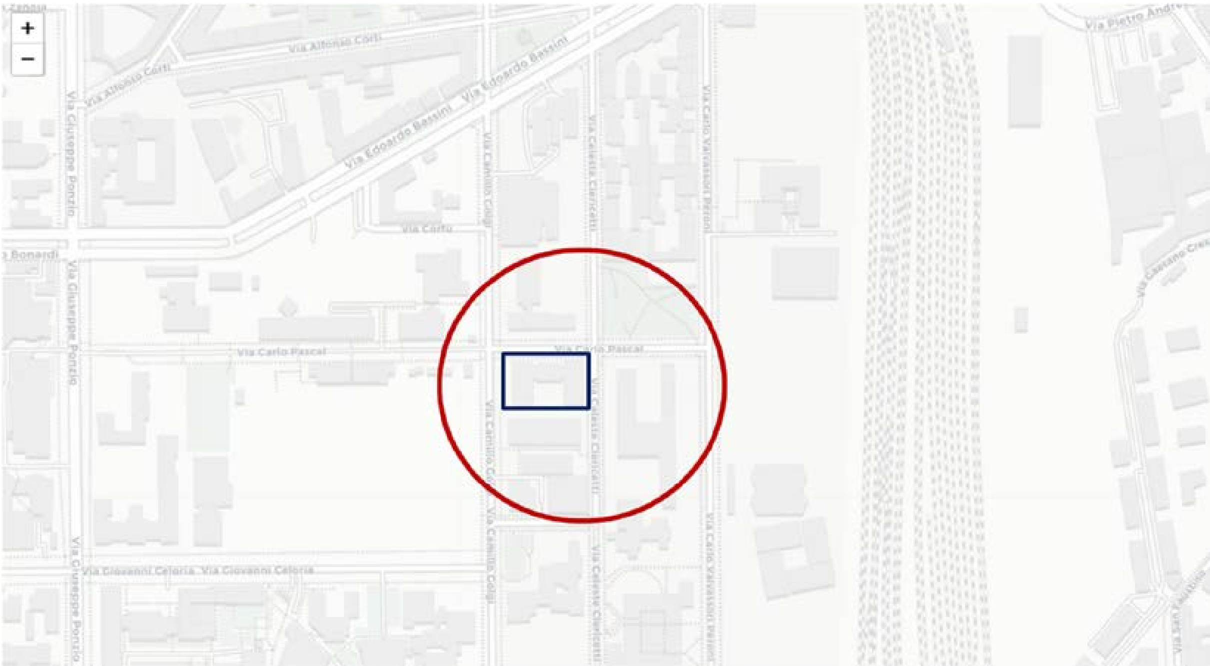

Fig. 7: Identification of the location of the assumed construction site and the area to be analyzed

To identify critical points, Figures 8 and 9 were analyzed, which report the output results obtained using the developed tools.

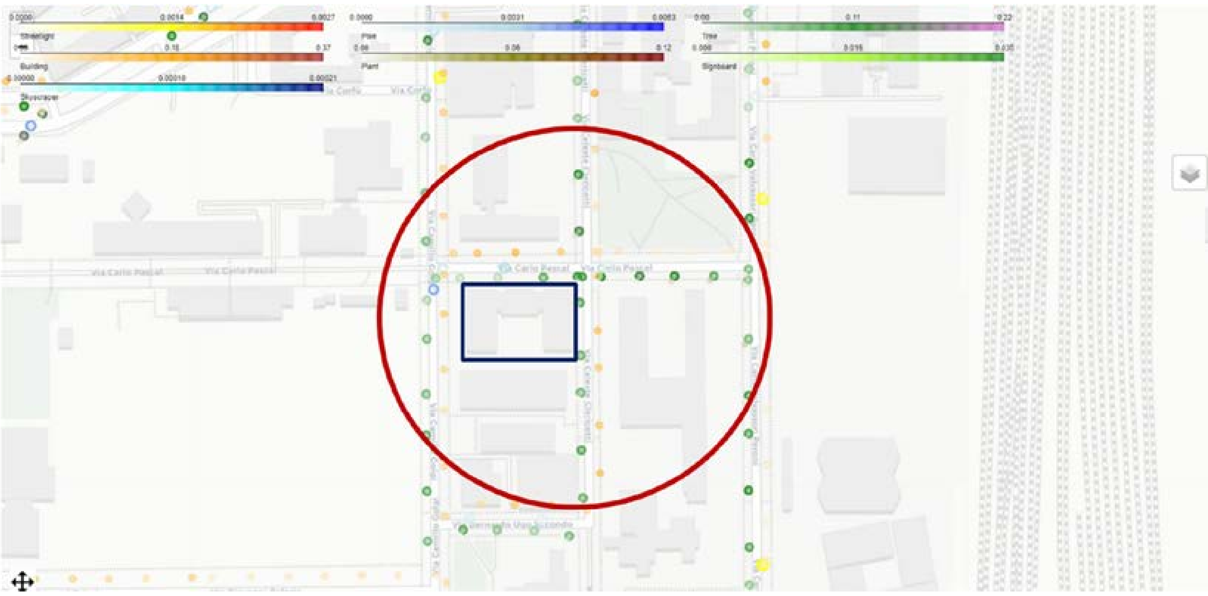

Fig. 8: Operational criticalities from tool Output 1

In Figure 8, there is a depiction of the constraints located near the intersection that has been identified as the area of analysis. The main issues that may arise are related to the presence of trees and buildings, which could potentially cause problems during future air handling procedures. Despite this, the arrangement of markers appears to be tidy and easily discernible, although this could be due to the high zoom used on the area and the existence of only two primary categories of elements.

In contrast, Figure 9 displays the outcomes obtained by utilizing tool number 2. Upon comparing these results with the previous image, it becomes apparent that reading the results, in this case, is neither rapid nor straightforward. The presence of numerous *ClusterMarkers* in one location hinders readability as one must open them to view specific locations. Additionally, this grouping only applies to Markers that belong to the same category. As shown in the figure, when multiple elements that belong to different categories overlap, their groupings also overlap. This can make it difficult to read the results when using the map at a higher zoom level than what is shown in the figure.

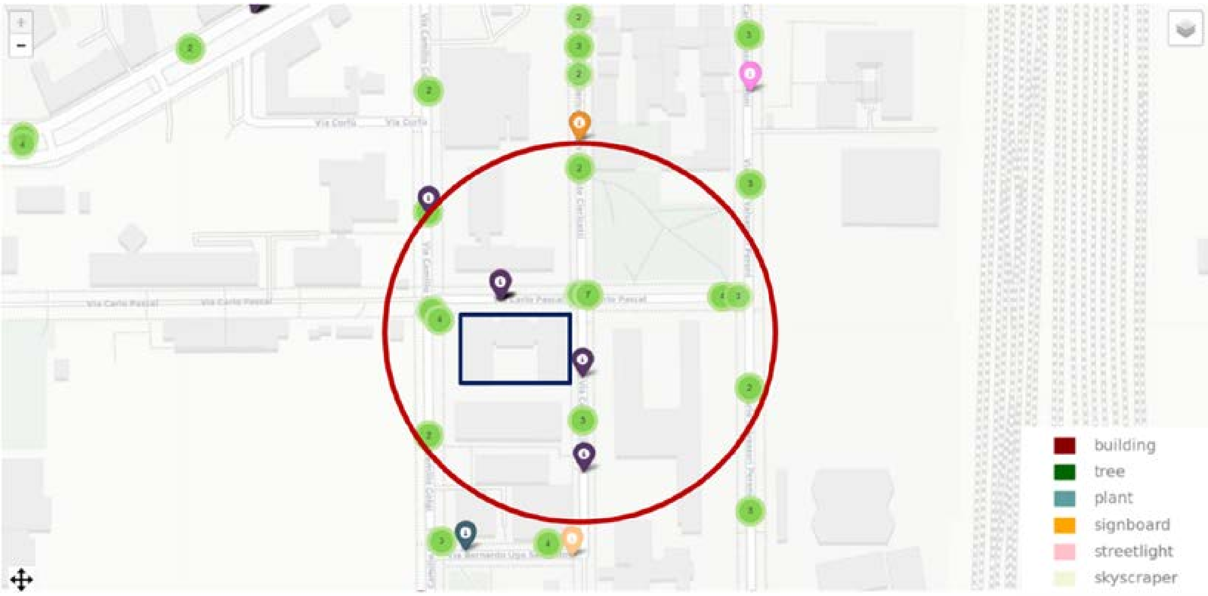

Fig. 9: Operational criticalities from tool output2

Although with the respective problems, identifying critical points in the area was relatively easy. Table 2 clearly shows the number of obstacles that could potentially cause issues during the operational phases of the future construction site. It is evident that the main obstacles are the buildings and trees adjacent to the area being analyzed, as previously mentioned.

Table 2: Number of elements recognized in the analyzed area

Element	Building.	Tree	Plant	Signboard	Streetlight	Skyscraper	Pole	Total
Total	23	32	6	0	3	0	8	69

Therefore, the proposed project has achieved its objective of reliably identifying objects and their positioning on the map with good results while acknowledging operational limits. However, it is important to note that the clear display of obstacle placement seen previously may not always be guaranteed. The first tool requires the application of a filter to provide a clear view of individual obstacles, although improvements have been planned for the overall view. On the other hand, the instrument with *ClusterMarkers* may have poor readability due to the overlap of different object groupings at the same point.

Typically, to assess potential risks in a particular environment, images are analyzed to identify any potential obstacles. Hence, it's crucial to study how the model segmented the images and locate these obstacles on output maps. The proposed code provides visual support for this analysis. Two of the images extracted by GSV for the analysis of Via Carlo Pascal (Figure 10) are shown below. Normally the designer would identify and manually report the possible obstacles, such as the presence of trees for air handling, or car parking in case the occupation of public land was necessary. Analyzing images through the image segmentation model, this procedure becomes assisted and facilitated. Comparing the original with the results obtained and shown in Figure 10, it is possible to see how elements such as cars, trees, sidewalks, and poles are recognized and marked distinctly. The classification of image pixels according to the elements for which the model has been trained can therefore be of fundamental help where the overlapping of objects makes it difficult to recognize them.

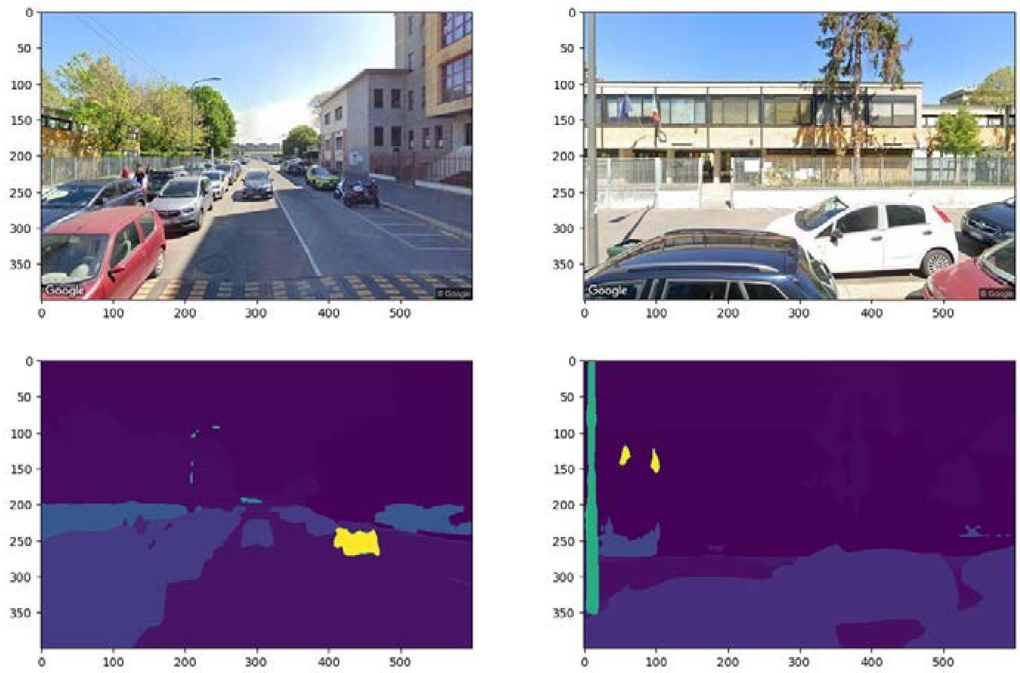

Fig. 10: Image segmentation results for the street analyzed in the example

However, by exploiting this type of approach for the analysis of criticalities, two fundamental limits can be identified, one technical and one "operational". The technical limit concerns the elements for which the model used has been trained. Indeed, there are about 150 objects that it can recognize, and not all of them are useful results for the purpose of this research. The solution to this limitation could be solved by developing a model trained to recognize a list of specific objects, related to the sector. Clearly, the realization is not immediate because in-depth knowledge of this type is beyond our competence.

The "operational" limit consists in not being able to rely entirely on the instrument. The validity of the results in terms of object recognition and positioning according to geographical coordinates has been obtained and demonstrated with excellent results. However, it should be remembered that an analysis carried out by this tool does not completely replace an analysis conducted directly by the designer. As stated above, the tool wants to be a support to ensure greater accuracy in the assessment of criticalities, but it is good to remember the existence of a margin of imprecision that only human experience can fill.

6. POSSIBLE IMPLEMENTATIONS AND CONCLUSIONS

The improvement and further development of the tool could lead to higher output quality and the implementation of additional functionalities. One of these functionalities could involve classifying objects based on their height and identifying them within the map as either aerial or surface constraints.

By adopting this classification approach and changing the output type, it would be possible to develop a tool that neglects the classification of objects according to their category of belonging. The recognized elements would still be positioned on the map based on their geographic coordinates; however, the color scale representing them would be based on the evaluation of their heights. Assuming to give the possibility to the user enters the reference value beyond which a constraint is considered aerial, the chromatic scale could then be defined based on this input that would represent the central value.

Nevertheless, regardless of the approach adopted for the development of such a tool, the utilization of artificial intelligence models, like the one employed in this study, has proven to be a proactive way to identify potential difficulties related to construction site organization and planning operations. However, it is essential to recognize that the images used as input, sourced from Google Street View (GSV), may have limitations in terms of quality and detail. Therefore, it is plausible to consider that the effectiveness and accuracy of the tool could be optimized by employing photographic surveys executed with appropriate instrumentation. This integration would enable the tool to provide more detailed and precise results concerning the construction site context, facilitating better analysis and identification of critical areas. In addition to the possibility of employing specific and higher-quality photographic surveys, considering the development of a dedicated AI model for this purpose could further enhance the capability to identify and address challenges inherent in construction site organization, offering a tailored solution for this domain.

In conclusion, adopting these measures would provide designers with a more sophisticated and efficient tool to navigate the complexities of construction sites, reducing the risk of errors or unforeseen complications, and enhancing overall decision-making in construction planning and management.

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GENERATIVE DESIGN INTUITION FROM THE FINE-TUNED MODELS OF NAMED ARCHITECTS' STYLE

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ABSTRACT: *This paper suggests the potential application of generative artificial intelligence-based image generation technology in the field of architecture, for early phase shape planning, using the styles of renowned architects. The study employed the following approaches: 1) Intensive image generation based on the styles of 20 architects to test the AI's recognition ability and image quality. 2) Additional training was conducted for architects with low recognition rates to construct an enhanced learning model in the quality of image generation. 3) In addition to generating architectural visualization images using existing architects' design styles, alternative styles were proposed through design combinations, aiming to concretize ambiguous idea communication in the early stages of design and enhance its efficiency. The study sheds light on the future prospects of applying this generative AI model in the field of architecture.*

KEYWORDS: *Design Style of Architects, Generative AI, Image Generation, Fine-tuning*

1. INTRODUCTION

In the field of architecture, visualization plays a crucial role in comprehending and evaluating complex design alternatives and spatial qualities [Greenberg, 1974]. Especially in the early design stages, it allows clear expression of design ideas and spatial concepts, enabling the identification and resolution of potential issues and facilitating effective communication among stakeholders [Akin, 1978]. Ultimately, early-stage visualization defines the design direction, enhances collaboration, efficiency, and leads to better outcomes. However, creating high-quality visualization images, particularly during the abstract design phases, remains challenging. While advancements in 3D modeling and rendering have improved the realism of visualizations, the process still demands time and specialized skills [Fonseca, 2017]. Currently, the emergence of AI and machine learning-based image generation models offers the ability to create images from text in a short timeframe. Applying this technology in the field of architecture has the potential to expedite the design process and foster creative design solutions.

Building upon this, our research focuses on the feasibility of generating architectural visualizations using AI-based image generation method. In Chapter 3, we tested the performance of the image generation AI model based on architects' styles, and in Chapter 4, we conducted additional training based on the test results. Finally, Chapter 5 demonstrates the practical applications of the Image generation AI including trained model.

2. BACKGROUNDS

2.1 Architectural visualization generation methods

Architectural visualization has evolved significantly over the years, transitioning from traditional manual techniques to embrace the power of digital technology. Historically, architects relied on hand-drawn sketches, physical models, and paintings to communicate their design ideas [Kehir AI-Kodmany, 2001; Atilola et al., 2016]. These methods, though expressive, had limitations in terms of scale, precision, and the time-intensive nature of creation. As architecture moved into the digital era, Computer-Aided Design (CAD) emerged as a game-changer, enabling architects to produce accurate and editable digital representations of their designs [Chiu, 1995]. It marked the beginning of a transformative shift in architectural visualization, offering architects the ability to iterate rapidly, explore design alternatives, and create highly detailed virtual models.

As technology continued to advance, architectural visualization expanded its horizons to encompass photorealistic rendering, three-dimensional (3D) modeling, and immersive experiences [Koutamanis, 2000]. Sophisticated

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Youngjin Yoo, Hyun Jeong, Youngchae Kim, Seung Hyun Cha and Jin-Kook Lee, *Generative Design Intuition from the Fine-Tuned Models of Named Architects' Style,* pp. 917-925, DOI 10.36253/979-12-215-0289-3.91

rendering software, bolstered by powerful Graphics Processing Units (GPUs), enabled architects to create high-fidelity visualizations that realistically conveyed materiality, lighting, and texture. 3D modeling provided a comprehensive understanding of spatial relationships [Eastman, 1999], offering architects the ability to manipulate and analyze their designs in a virtual environment [David et al., 2022]. This progress in technology not only increased the efficiency of the design process, ultimately leading to better-informed design decisions and more visually impactful presentations.

2.2 Image generation artificial intelligence (AI)

In 2014, Generative Adversarial Networks (GANs) emerged as a dominant paradigm for image generation research. GANs showcase their prowess by creating realistic images through competitive training involving a generator and a discriminator [Goodfellow et al., 2014]. As the stability of GAN training methods improved, the focus shifted towards generating images with specific attributes and refining the generated outputs [Karras et al., 2020]. These techniques have been applied to comprehend the information conveyed in architectural drawings, making it interpretable for computers. [Kim et al., 2019; Kim et al., 2020]

Since 2020, within the diverse landscape of image generation AI platforms, several notable options have emerged. Midjourney [Oppenlaender, 2022] specializes in style blending, empowering users to influence the fusion of multiple styles within the generated images. DALL-E 2 [Ramesh et al., 2022] creates images from textual descriptions, showcasing the potential to transform words into visuals, despite occasional inconsistencies. In contrast, Stable Diffusion [Rombach et al., 2022] leverages a diffusion model, ensuring stability during training and providing the capacity to manage image quality and intricacy. It shows immense promise in bridging the gap between abstract architectural concepts and their visual manifestation.

Among these, Stable Diffusion holds particular promise for architectural visualization research, given its ability to handle complex image transformations, align well with architectural subtleties, provide stability during training, and offer control over output quality and detail [Oppenlaender et al., 2023; Borji, 2023]. This positions Stable Diffusion as a potent tool to bridge the gap between architectural concepts and visual representation, redefining how architects approach their work and streamlining the creative process.

2.3 Potential for architectural visualization automation

There has been extensive research in image generation AI; however, its full potential for architectural visualization has yet to be realized. This research introduces a novel approach to architectural visualization using image generation AI models, emphasizing their transformative impact on this field. By harnessing advanced machine learning techniques, the study explores innovative methods to enhance architectural visualization, including text-to-image generation, which creates images from textual descriptions [Saharia et al., 2022]. This capability enables the generation of highly realistic images, making it a versatile tool with significant potential for various architectural visualization applications.

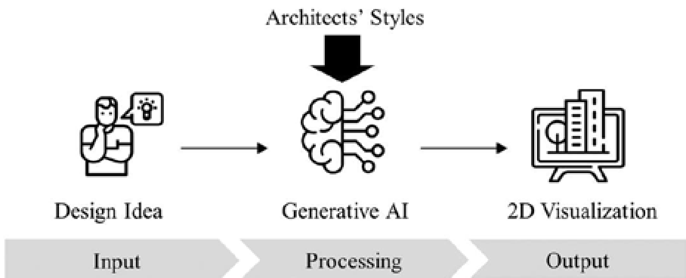


Fig. 1: Research approach: Image generation AI based architectural visualization

3. INTENSIVE TEST OF IMAGE GENERATION AI WITH ARCHITECTS' STYLE

3.1 Image generation test for architects' styles

Image generation artificial intelligence (AI), particularly Stable Diffusion (SD), involves two primary methods. The first method generates images from a text prompt, known as text-to-image generation. The second method, image-to-image generation, requires a seed image in addition to text prompts to generate images based on both inputs. In this paper, we focus primarily on text-to-image generation which generates images (Img_G) using the

"$generate()$" function, requiring a AI model (M), parameters ($Param$), and prompts (P_t).

$$generate(M, Param, P_t) = Img_G \tag{1}$$

$$Param = \{resolution, sampling\ method, sampling\ steps, CFG\ scale\} \tag{2}$$

$$P_t = \{SDP, RQP\} \tag{3}$$

The $Param$ consist of four components: $resolution$, determining the image size in pixel; $sampling\ method$, selecting method for image extracting from latent space; $sampling\ steps$, defining the number of extraction stages; and Classifier-free guidance scale ($CFG\ scale$), specifying the influence level of the prompt. The P_t consist of Scene Description Prompts (SDP), describing the target scene, visual composition, and graphic style, and Resolution Quality Prompts (RQP), adjusting the image's quality. Additionally, to prevent errors, each prompt composition includes negative prompts to specify what should be excluded. Table 1 provides example prompts corresponding to its composition.

Table 1: Prompt composition and its examples.

Composition of P_t	Positive Prompt example	Negative prompt example
Scene description prompts (SDP)	A residential house, professional photograph, photorealistic rendering, deep depth of field, high-key lighting, two-point perspective, etc.	Commercial buildings, painting, sketch, bird's-eye view, isometric, portrait, cropped view, etc.
Resolution quality prompt (RQP)	realistic shadows, enhance-detail, v ray rendering, full HD, masterpiece, highly detailed, high quality, 8k, etc.	low quality, too much noise, normal quality, watermark, blurry textured, blurry, noise, faint, text, etc.

In this section, we tested the performance of the text-to-image method defined earlier for generating architectural visualization. We randomly selected 20 architects who have received architectural awards or have had significant international influence, and generated images reflecting their styles. While additional descriptive keywords could enhance image quality by further delineating each architect's features, we excluded them for a clearer assessment of the default model's architect's style recognition capabilities. Instead, we used only the prompt "Architect's name-inspired residential house" and prompts associated with photorealistic rendering, commonly used in architectural visualization. We generated approximately 100 to 150 images for each architect in a local PC environment, with a resolution of 1024 by 512 pixels. The generated results are summarized in Figure 2.

None style "A residential house" | Low Recognition "Renzo Piano-inspired residential house" | High Recognition "Frank Gehry-inspired residential house"

Fig. 2: Result of text-to-image generation test

3.2 Findings and ongoing inquiry in image generation AI

The generated results were assessed based on three criteria for their alignment with P_t. This assessment encompassed: (1) Style fidelity, which measures the accuracy of depicting the design characteristics of architects, (2) Domain fidelity, which verifies the representation of unique features for residential houses, and (3) Image quality, assessing the extent to which the photorealistic style rendering prompt was reflected in terms of graphic style, composition, and resolution.

The image generation test results indicated that the current SD model achieved a high level of domain fidelity and overall image quality. However, it exhibited low recognition for specific architects' styles, regardless of their prominence, resulting in lower quality and less detailed images of generic Western-style residential houses without any corresponding style features. As a result, the need for further additional training of the existing image generation model to address these limitations in recognizing certain architects' styles became evident. Motivated by this necessity, we conducted additional training, specifically targeting Architects' design styles, as depicted in Figure 3.

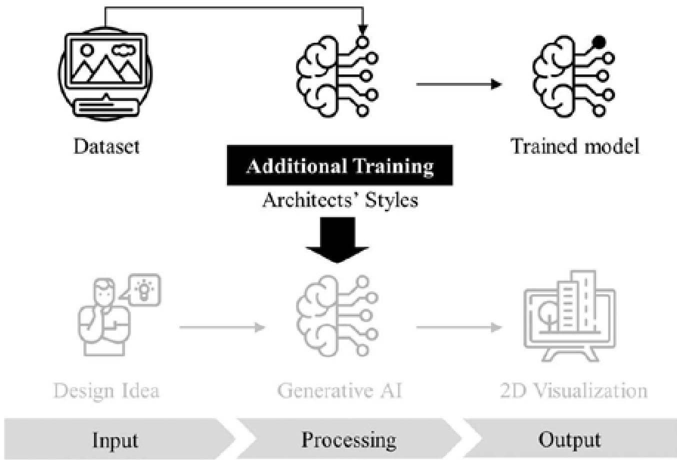


Fig. 3: Research Overview: Additional training for architects' styles

4. ADDITIONAL TRAINING FOR ARCHITECTS' STYLES

4.1 Additional training and data preparation

If the majority of generated images (Img_G) do not match the target image group (Img_t), it is required to replace the current model (M) with an alternative model (M'). This replacement can involve either substituting the model or enhancing it through further training. In this chapter, Low Rank-Adaptation (LoRA) approach [Hu et al., 2021] is employed for additional training, aiming to improve the recognition of specific architects' styles and to generate images that appropriately belong to the Img_t. The target model (M_t) is developed using the "$train()$" operator, based on the base model (M), hyperparameters ($Hyperparam$) and a target training dataset (D_t).

$$Most\ of\ Img_G \notin Img_t \Rightarrow M' \rightarrow M \quad (4)$$

$$train(M,\ Hyperparam,\ D_t) = M_t \in M' \quad (5)$$

Hyperparameters play a significant role in both the model's learning process and the subsequent performance of the M_t. We specifically focused on three crucial hyperparameters: the training batch size (BS_t), the number of epochs ($epoch$), and the learning rate (α). At the same time, the effectiveness of additional training relies on a high-quality dataset (D_t) containing image data (Img_D) along with corresponding annotation text files (Txt_D).

$$Hyperparam = \{BS_t, epoch, \alpha\} \quad (6)$$

$$D_t = \{Img_{D1}, Txt_{D1}, \dots, Img_{Dn}, Txt_{Dn}\} \quad (7)$$

The additional training process, as depicted in Figure 4, involves two essential steps: (1) dataset preparation [Abdallah et al, 2017] and (2) training [Hu et al., 2021]. During the dataset preparation phase, meticulous training data collection is required to ensure alignment with P_t. Preprocessing phase aids in removing unnecessary content that might disrupt the training process. It is crucial to ensure content quality of training data, and the correspondence between Img_D and Txt_D. Following this, the Txt_D is paired with the respective Img_D, and the prepared D_t is then trained using the specified $Hyperparam$.

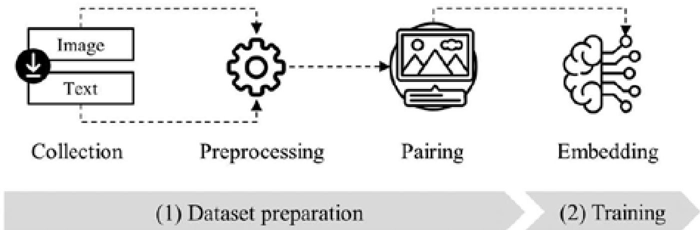


Fig. 4: Additional training process

4.2 Additional training of existing model with architects' styles

In this chapter, we provided additional training to architects who received low or no recognition in the image generation test discussed in Chapter 3. We conducted a few-shot learning using the previously defined training approach. By incorporating the trained LoRA model (M_t) into the image generation function, the possibility that generated images ($Img_{G'}$) closely resemble the designated Img_t is notably improved compared to the previous results. When utilizing M_t, in addition to M, it is crucial to input the application weight (W), a value ranging from 0 to 1, where 0 represents 0% and 1 represents 100%.

$$generate(M' \vee M(M_t, W),\ Param,\ P_t) = Img_{G'} \tag{8}$$

We compared the performance of the default model (M) with the trained model (M_t) by generating images with both. The image generation process followed equation (8), and the parameters (Param) and prompts (P_t) used for image generation remained consistent with those used in Chapter 3. As shown in Figure 5, the existing model had very low recognition rates for certain architects, so even with a full weight, the specific features of those styles were not represented. However, when using the trained model, these features are correctly displayed, and their application is proportional to the weight. The additional training allows us a wider range of style options that the original model could not achieve.

Default model 1.0 "SANAA-inspired residential house" | Trained model 0.5 "SANAA-inspired residential house" | Trained model 1.0 "SANAA-inspired residential house"

Fig. 5: Additional training results: SANAA style

5. DEMONSTRATIONS

Our investigation revealed that AI-driven image generation rapidly produces high-quality architectural visualizations from text prompts, empowering architects to easily create reference images and visualizations from the start of the design process. This chapter demonstrates the practicality of Image Generation AI, particularly Stable Diffusion, across various architectural styles. The three applications include: (1) building additional training models for desired architects' styles, (2) generating architectural visualizations applying an individual architect's style, and (3) generating style alternatives by combining more than two styles.

5.1 Implementation of different styles through additional training

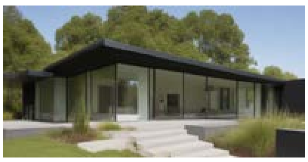
In this scenario, we employ image generation AI to incorporate diverse architects' styles, providing users with desired visualization outcomes through additional training. In this chapter, we conducted additional training following the process outlined in Figure 4, targeting five architects with very low recognition rates, aiming to enhance the model's level of detail. To ensure high-quality training images, we sourced project photographs from reputable sources, such as Architects' official websites, focusing on full facades in 1-point or 2-point perspective. Preprocessing involved image resizing and the removal of excessive information. Text data was constructed for each image, extracting from interviews with architects, expert analyses, and prior research about their styles. Each target style was trained with 15-25 datasets in average, with hyperparameters {1, 100, 0.0001}, and it took 8-15 minutes per each training.

The resulting model files, incorporated into the existing model, produce architectural exterior images closely mirroring architects' design styles, even when data is limited. In this chapter, we generated five M_t files, each representing the styles of different architects, capable of producing high-quality images comparable to those shown in table 2 of chapter 5.2.

5.2 Visualization of design alternatives from text prompts

This scenario describes how we acquired a diverse set of creative reference images representing different architects' design styles. In this chapter, we applied the M_t developed in the previous chapter to M in order to generate architectural visualizations based on the styles of 20 selected architects, using the same prompts as those used in the image generation test in chapter 3.1. We generated approximately 100 to 150 images for each architect based on equations (1) and (8), with the parameters {(1024, 512), Euler α, 20, 7}. These images, as demonstrated in Table 2, accurately reflect not only their respective styles but also maintain the essential characteristics of residential buildings, even for architects with little prior experience in residential projects. These generated outputs provide a rich source of diverse and concrete ideas and inspirations right from the initial stages of architectural design, streamlining communication and facilitating the design process.

Table 2: Resume of generated visualizations from text prompts

Input prompt	Output		Descriptive Keywords
I.M. Pei-inspired residential house, Photorealistic rendering prompt set			Modernist, minimalist, geometric, cultural fusion, monumental, symmetrical, glass and steel, iconic, etc.
Renzo Piano-inspired residential house, Photorealistic rendering prompt set			Lightness, Transparency, industrial materials, fluidity, civic and public focus, open spaces, etc.
Le Corbusier-inspired residential house, Photorealistic rendering prompt set			Modernism, functionalism, free façade, open floor plans, concrete, horizontal windows, etc.
SANAA-inspired residential house, Photorealistic rendering prompt set			Minimalist, subtle elegance, organic forms, conceptual simplicity, fine steel structure, white color, transparency, etc.
Shigeru Ban-inspired residential house, Photorealistic rendering prompt set			Sustainability, paper architecture, wooden modular structure, organic design, grid, organic forms, patterns, etc.
Frank Lloyd Wright-inspired residential house, Photorealistic rendering prompt set			Organic architecture, prairie style, horizontal lines, flat roofs, clerestory windows, cantilevered overhangs, etc.
Antoni Gaudi-inspired residential house, Photorealistic rendering prompt set			Curved lines, mosaic and tilework, nature-inspired design, whimsical details, unconventional forms, use of color, etc.
Mies van der Roe-inspired residential house, Photorealistic rendering prompt set			Minimalism, steel and glass, open floor plans, linear and geometric design, Bauhaus influence, international style, etc.

Ex) Photorealistic rendering prompt set = *Positive prompts:* professional photograph, photorealistic rendering, realistic, enhance-detail, v ray rendering, full HD, masterpiece, highly detailed, high quality, 8k, two-point perspective, exterior view, full shot, deep depth of field, f/22, 35mm, high-key lighting, natural lighting, realistic shadows; *Negative prompts:* low quality, bad proportion, awkward shadows, unrealistic lighting, pixelated textures, too much noise, unrealistic reflections, normal quality, watermark, bad perspective, confusing details, blurry textured, blurry, noise, cloudy, faint, text.

5.3 Combination between architects' styles

This scenario illustrates the creation of diverse image references by blending multiple architectural styles, resulting in novel and previously unseen styles. Users can expand their architectural image references using image generation AI by combining the styles of two or more architects. The P_t and $Param$ for these operations are the same as those in other image generation cases, except for the SDP (Scene Description Prompts), which is observable in Table 3. This setup allows for a comparison between the results of applying a single style and the application of multiple styles, facilitating an assessment of the progress of the operations.

Table 3: Example of combination of architects' styles using text-to-image method

Classification		Mono-style: SANAA style	Mono-style: Luis Barragan style	Multi-style: SANAA and Barragan
Input	Model	Trained model		
	Parameters	Resolution: 1024 × 512 / Sampling method: Euler a / Sampling steps: 20 / CFG scale: 7		
	Prompts	SANAA-inspired residential house, Photorealistic rendering prompt set	Luis Barragan-inspired residential house, Photorealistic rendering prompt set	SANAA and Luis Barragan-inspired residential house, Photorealistic rendering prompt set
Output				
Descriptive Keywords		Minimalist, elegance, sensitivity, fine steel structure, white color, simplicity, transparency, etc.	Minimalism, color, geometry, concrete, simplicity, play of light and shadow, etc.	Fine structures, colorful, rectilinear, concrete, simplicity, geometry, etc.

As shown in Table 3, the combination of two different styles is evident and noticeable. When the curvilinear style of SANAA is combined with the rectilinear style of Luis Barragan, the curvilinear aspect of SANAA becomes less pronounced. Additionally, the resulting style incorporates the color palette and materiality of Luis Barragan, along with SANAA's distinctive design feature of thin structures. These findings demonstrate that image generation AI can create new alternative styles based on existing ones, potentially generating a variety of additional alternatives.

6. CONCLUSION

This research marks the initial steps in exploring the potential of architectural visualization through image generation AI, with a specific focus on the Stable Diffusion model. The study underscores the significant impact of image generation AI, particularly in the field of architecture and its application in early-stage architectural visualization. Leveraging deep learning and image generation techniques, we trained the model to capture the distinctive styles of renowned architects, using this knowledge to visualize typical residential houses. Our testing revealed that while the default SD model generally produces high-quality architectural visualizations with domain fidelity, it does face limitations in recognizing the unique styles of architects. However, we demonstrated that these limitations can be improved through additional training, highlighting the powerful potential of image generation AI.

This approach plays a pivotal role in bridging the gap between abstract design concepts and tangible visual representations, empowering architects to effectively convey their creative ideas. Integrating AI technology into architectural visualization broadens creative possibilities, enabling architects to explore a diverse range of design alternatives. Looking ahead, further research is essential to develop comprehensive and refined methods for additional training, expanding beyond architects' styles to other targets. Additionally, the focus should be on enhancing the accessibility and utility of this technology by exploring other generation methods, such as image-to-image, and the development of user-friendly tools.

7. AKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MIST) (No. NRF-2022R1A2C1093310)

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PLANNING ALTERNATIVE BUILDING FAÇADE DESIGNS USING IMAGE GENERATIVE AI AND LOCAL IDENTITY

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ABSTRACT: *This paper describes an approach utilizing Generative AI to support diverse design alternatives for building facades based on the local identity. Extensive research is currently being conducted for exploring the applications of LLM-based generative AI models to diverse kinds of visualizations. By applying generative AI to facade design, the study aims to develop additional training models that generate alternative design options reflecting local identity, facilitating the acquisition of remodel design images from multiple texts and images. Building facades in cities and regions are essential for people's aesthetic perception and understanding of the local environment, enabling the recognition and differentiation of specific areas from others. Therefore, implementation method of the additional training model based on generative AI in this study, reflecting this, can be summarized as follows: 1) collection and pre-processing of image data using Street View, 2) pairing text data with image data, 3) conducting additional training and testing with various inputs, 4) proposing relevant application methods. This approach can be expected to enable efficient communication of design at an early stage of the architectural design process beyond traditional 3D modeling and rendering tools.*

KEYWORDS: *Building facade, Generative AI, Local identity, Design alternative, Additional Training Model*

1. INTRODUCTION

Recently, platforms such as 'Midjourney,' 'Dreamstudio AI,' and 'Stable Diffusion' have been developed and used alongside Large Language Model (LLM) based platforms like 'ChatGPT' (OpenAI, 2022) to generate images using Diffusion models. These platforms are provided in accessible forms for the public, and their interfaces and functionalities are consistently updated. These platforms are based on generative artificial intelligence, allowing users to easily create desired images creatively by providing prompts and adjusting settings. This generative AI-based image creation approach is not only applied in design and art fields but also in various other domains. It is also being employed in architecture, generating images of diverse buildings and spatial designs in various styles, contributing to applied research.

In this study, the aim is to apply the image generation capability of generative artificial intelligence to obtain facade images of buildings. Furthermore, this involves creating building images with regional design identities, aiming to establish an approach for more efficient utilization during the initial building planning and design stages (Relph, 1976). This approach focuses on commercial buildings, allowing for the swift acquisition of creatively designed facade images in the early architectural phases by adjusting the degree of regional identity incorporation.

The research follows the following methodology: Initially, to evaluate the effectiveness of the image generation model, a repetitive process of image generation was conducted, resulting in the creation of a substantial number of images for testing. Based on these results, it was evident that additional training of the basic generative AI model was necessary. Subsequent steps for this additional training were carried out as follows: 1) Constructing a training dataset, 2) Conducting additional training and generating model files, 3) Confirming and utilizing result images incorporating the additional training model files. This was executed in the form of additional training utilizing the Diffusion-based model. The additional training was built upon LoRA (LoRA: Low-Rank Adaptation of Large Language Models), and by adjusting hyperparameters, it was ensured that high-accuracy images were generated. Following this, the generated additional training model files were applied to generate and confirm result images, suggesting an approach to visualize these images in the early architectural stages.

2. BACKGROUND

2.1 Image Generative AI

Since 2020, diffusion process-based techniques have gained prominence in the arena of deep learning-driven image synthesis. These approaches iteratively update pixel values to progressively generate images (Ho, Jain, & Abbeel, 2020). Concurrently, scholars have immersed themselves in artificial intelligence models that facilitate the

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Hayoung Jo, Sumin Chae, Su Hyung Choi, Jin-Kook Lee, *Planning Alternative Building Façade Designs Using Image Generative AI and Local Identity,* pp. 926-932, DOI 10.36253/979-12-215-0289-3.92

transformation of textual data into visual representations, marking significant progress in the domain of image generation (Ramesh, Dhariwal, Nichol, Cuy, & Chen, 2022; Saharia, Chan, Sawena, Li, Whang, Denton, … & Norouzi, 2022; Rombach, Blattmann, Lorenz, Esser, & Ommer, 2022).

While considerable scholarly inquiry has been devoted to deep learning-assisted image synthesis, its potential in the realm of architectural design visualization remains largely untapped (Kim, & Lee, 2020). This investigation introduces an innovative proposition for architectural design visualization, harnessing the capabilities of AI-driven image synthesis models and recognizing their transformative impact in the landscape of image generation. Through the application of these advanced machine learning techniques, this section aims to explore novel pathways to enhance architectural design visualization via AI-powered image training models.

With the advancement of the LLM model and the image synthesis technology, the feasibility of producing architectural visualization images based on provided textual input has become achievable. Termed as text-to-image synthesis, this process possesses the ability to generate highly realistic images, making it a versatile instrument for generating a diverse range of architectural visualization content. As AI technology continues its evolution, the role of text-to-image synthesis is expected to play a crucial role in the architectural domain. Consequently, the integration of AI-driven image synthesis enhances the potential for imaginative exploration beyond traditional methodologies.

2.2 New opportunities for Architectural Visualization

Architectural visualization, such as photorealistic images, plays a crucial role in enhancing communication within the field of architecture (Lee, Lee, Kim, & Kim, 2023). Firstly, photorealistic renderings transcend mere geometric massing, enabling architects to vividly convey their design intentions to clients. These images serve as intermediaries between architectural drawings and experiential aspects of architectural spaces by presenting architectural concepts in a reality-like manner (Kim, & Lee, 2022). Such visualizations facilitate shared understanding among stakeholders. Secondly, visualization empowers not only architectural professionals but also stakeholders, clients, and the public to grasp architectural visions that transcend architectural terminology and technical complexity. Visualized images like photorealistic renders enable individuals to comprehend the interaction between planned architectural attributes, ambiance, and the surrounding environment, enabling informed decision-making based on information. Transitioning from geometric massing to photorealistic render images allows for a more universal and comprehensive communication of intricate architectural concepts, thus promoting smoother communication.

In summary, integrating visualization images like photorealistic renderings into the architectural design process enables efficient communication in the early stages of architecture, induces information-based decision-making, and enhances creative design. While traditional architectural visualization relied on complex technical processes and necessitated GPUs and specialized hardware, leveraging generative AI, as discussed earlier, allows for obtaining numerous detailed visualization images effectively without the need for separate GPU renderers.

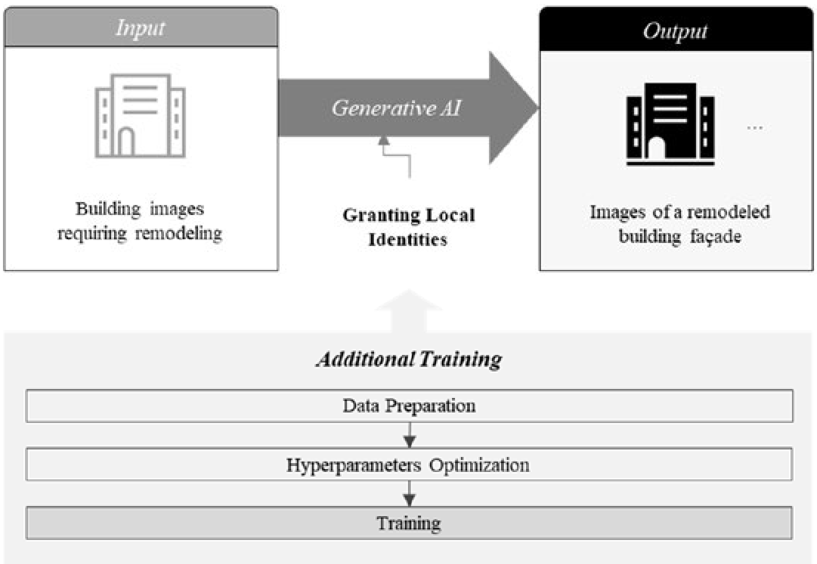


Fig. 1: Overview of the approach proposed in this study.

The following section examines the application of such generative artificial intelligence to architecture, exploring the potential of generating architectural images. This investigation, as outlined in the introduction, focuses on the design aspect of building facades within the realm of architectural elements (Kier, 1984). Specifically, this inquiry aims to determine the feasibility of effectively generating architectural visualization images by emphasizing regional identity as a pivotal design consideration within building facade design.

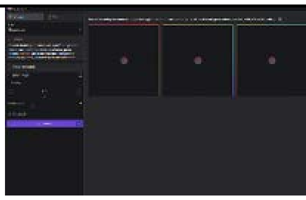
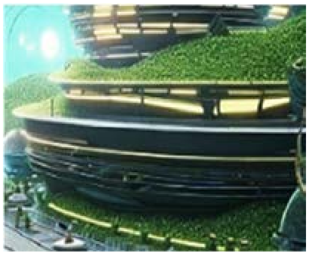
3. TEST ON BASIC IMAGE GENERATION MODELS

3.1 Test Generative AI Platforms

Various platforms are being developed using generative artificial intelligence to make it easily accessible for the public. These platforms utilize different interfaces and base models, resulting in a range of image generation platforms that cater to various user requirements such as freedom of generation, design style of images, sizes, and image quality. In this paper, we utilized the commonly used platforms 'Midjourney,' 'Dreamstudio AI,' and 'Playground AI' to understand their respective interfaces, directly engage with them, and explore their features and specific functionalities.

Among these three platforms, the latter two platforms, excluding 'Midjourney,' offer partial free usage for image generation, with subscriptions or purchases required for more extensive usage. Each interface provides common features including the option to select various image styles like 'Enhance,' 'Anime,' 'Photographic,' 'Comic book,' as well as the ability to create Positive and Negative prompts. All platforms also offer the functionality to adjust specific settings to generate images. Additionally, they provide an "Image-to-Image" feature wherein users can input desired images to generate text based on the images, resulting in the creation of different images. By utilizing these functionalities, one can quickly generate images tailored to specific requirements. For instance, when aiming to acquire building facade images as shown in Table 1, it becomes possible to generate images that incorporate more creative ideas. The following section will proceed with an examination of building facade image generation through detailed testing, utilizing prompts that encompass greater specificity and domain knowledge.

Table.1: Investigation of the interfaces of prominent platforms for image generation models and examples of generated images (The generated images from Midjourney and Dreamstudio AI are provided by openart (https://openart.ai/), while the examples generated by Playground AI are based on similar prompt-based approaches).

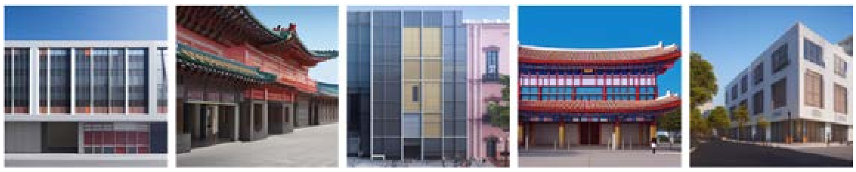
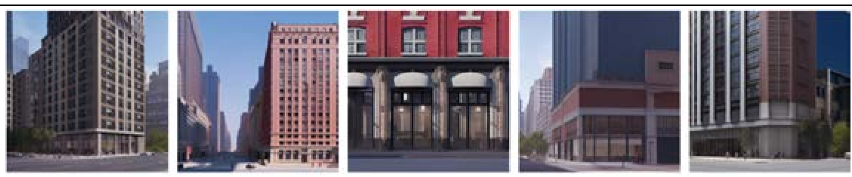
		Midjourney	**Dreamstudio AI**	**Playground AI**
Web Interface				
INPUT	Key Prompt		Building Façade Image	
OUTPUT	Generated Images			

3.2 Testing of Façade Image Generation Reflecting Local Design Identity

In this section, we aim to investigate whether it is possible to generate facade design images that reflect regional identity using generative artificial intelligence. To achieve this, we conducted image generation tests based on text prompts using the existing basic model grounded in Diffusion. The tests were divided into three main categories: facade images of buildings without region-specific text input, facade images of buildings reflecting Korean style, and facade design images of commercial buildings in Manhattan. The goal was to compare the generated images for these three categories. For each category, we utilized key prompts such as "Building Facade," "Building Façade reflects Korean style," and "Building Façade reflects Manhattan style." Additionally, we employed prompts to enhance image quality to generate results like those in Table. 2.

By utilizing the existing generative artificial intelligence-based model, it was observed that when region-related text prompts were input, corresponding images could generally be generated. However, this primarily resulted in localized images, and it was found that the generated facade design images did not exhibit diverse variations reflecting the unique images associated with each region. For instance, in the case of Korean facade images, predominantly images of buildings featuring traditional Eastern style hanok architecture were generated. Therefore, in the subsequent section, we proceed to construct a model through fine-tuning of the existing generative artificial intelligence model, aiming to determine if image generation with a focus on regional facade design identity can be achieved.

Table. 2: Example of generating building facade images with regional names using the basic generative AI model

No.	Key Prompts	Generated Images
1	Building Facade	
2	Building Façade reflects Korean style	
3	Building Façade reflects Manhattan style	

4. CONSTRUCTION AND UTILIZATION APPROACHES OF THE ADDITIONAL TRAINING MODEL

4.1 Additional Training and Testing of Local Facade Design Identity Model

In this section, we aim to investigate the generation of facade design images that reflect regional identity by conducting additional training of a generative artificial intelligence model within the scope of the target region. Model construction utilized the Diffusion-based model implemented on the foundation of LLM (Large Language Model) for additional training. This additional training process can be summarized into three main stages: 1) Data Preparation, 2) Model Training, and 3) Image Testing and implementation. Data preparation involved pairing image and text data. For efficiency in image data collection, street-view functionality from portal sites API was employed, as described earlier. However, the distorted nature of 360-degree panorama images from street-view led to generating indistinct façade images, lowering image quality and accuracy. To address this, image preprocessing was conducted to correct distortions, resize images to a consistent size, and then pair them with text data to compile the dataset.

For model training, the LoRA (Low-Rank Adaptation of Large Language Models) approach was adopted to facilitate additional training of the Diffusion model (Hu, Shen, …& Chen, 2021). LoRA allows for rapid additional training of existing large-scale models within a short timeframe, without significant demands on GPU performance. Unlike other methods, LoRA generates relatively smaller additional training model files and offers the advantage of easily assessing style incorporation through adaptability changes in the model files. Thus, in this research, LoRA is employed to construct additional training models, optimizing hyperparameters to generate highly accurate images with minimal distortion. The optimization of hyperparameters, including adjustments to epochs, training batch size, and caption extensions, aims to enhance the accuracy and quality of the resulting images.

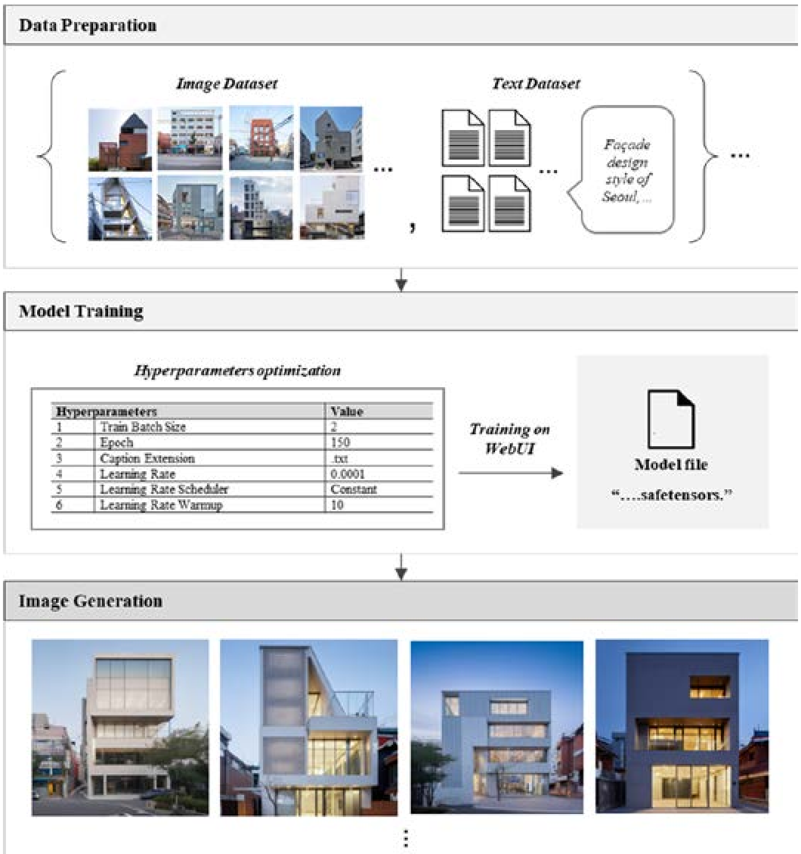


Fig. 2: Construction Process of the Additional Training Model

When conducting additional training using LoRA, model files with the extension ".safetensors" are generated. Inserting these generated model files into the model management folder of the Stable Diffusion Web-UI enables the models to function in the format of a text prompt, allowing the generation of desired images alongside the text data used for training. Furthermore, by adjusting the adaptability of the generated model files, a wide array of creative design images can be produced. Applying the additional training model file created using exterior images and text data of commercial buildings in the Seoul area, according to different weight values, results in images as shown in Table 3. When applying a weight of 0.1, images of buildings with views from different angles beyond the front facade are generated. As the weight approaches 1.0, images distinctly reflecting Seoul's facade design style are generated.

Table. 3: Test of Additional Training Models according to each weight

Weight	Generated Images			
0.1				
0.5				

1.0	

4.2 Utilization Approaches of the Additional Training Model File

In this section, we demonstrate one example of an approach that can be applied in the early stages of architecture using the constructed additional-trained model files. We validated the images that could be generated by applying the model files using actual facade images of buildings in Seoul. When applying this method and providing detailed prompts, it was observed that images reflecting Seoul's facade design style could be generated.

Table. 4: Image generation from Each Input Image

		A	B	C
INPUT	Key Prompt	Building Façade reflects Seoul style		
	Detailed Prompt	Modern design style	An arched window	Red brick finish
	Utilized Model file	***Building Façade Design Style of Seoul.safetensors***		
	Images			
OUT-PUT	Generated Images			
		…	…	…

5. CONCLUSION

In the initial design stages of existing buildings, facade design plans have traditionally relied on manual efforts by designers and architects, or methods involving 3D modeling tools and high-performance GPU renderers. These methods have necessitated repetitive tasks to facilitate communication with clients. This study discusses an approach that leverages the recent advancements in generative artificial intelligence, which is being actively applied in related fields, to generate facade design alternatives using image generation AI. Within the context of this research, we propose an approach that enables quick confirmation of building facade design plans reflecting regional facade identity in the early design stages and the generation of numerous alternatives.

According to the approach proposed in this study, it was confirmed that utilizing image generation AI can rapidly confirm building facade design plans, incorporating regional facade identity, and produce a multitude of alternatives. This approach was demonstrated through applying Seoul's facade design style using actual building images to showcase its effectiveness. Consequently, exceptional visualization images were generated.

Although there may be limitations in this study, particularly in constructing a fine-tuned model focused on Seoul, it holds significance in its potential to create and explore more diverse and domain-specific models using this methodology. This opens the door for further application-oriented research, leveraging more specific characteristics and domain knowledge to refine the approach.

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ACKNOWLEDGEMENT

This work is supported in 2023 by the Korea Agency for Infrastructure Technology Advancement (KAIA) grant funded by the Ministry of Land, Infrastructure and Transport (Grant RS-2021-KA163269).

EARLY DETECTION AND RECONSTRUCTION OF ABNORMAL DATA USING HYBRID VAE-LSTM FRAMEWORK

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ABSTRACT: *Early failure detection and abnormal data reconstruction in sensor data provided by building ventilation control systems are critical for public health. Early detection of abnormal data can help prevent failures in crucial components of ventilation systems, which can result in a variety of issues, from energy wastage to catastrophic outcomes. However, conventional fault detection models ignore valuable features of dynamic fluctuations in indoor air quality (IAQ) measurements and early warning signals of faulty sensor data. This study introduces a hybrid framework for early failure detection and abnormal data reconstruction applying variance analysis and variational autoencoders (VAE) coupled with the long short-term memory network (VAE-LSTM). The periodicity and stable fluctuation of IAQ data are exploited by variance analysis to detect unusual variations before failure occurs. The IAQ dataset which is corrupted by introducing complete failure, bias failure and precision degradation fault is then used to verify the feasibility of the VAE-LSTM model. The results of variance analysis reveal that unusual behavior of the data can be detected as early as 12 hours before failure occurs. The reconstruction performance of the developed method is shown to be superior to other methods under different abnormal data scenarios.*

KEYWORDS: *Early failure detection, Abnormal data reconstruction, Variational autoencoder (VAE), Long short-term memory network (LSTM), Sustainable IAQ management*

1. INTRODUCTION

Indoor air quality (IAQ) in public buildings is regarded as a hot study topic as it has a big impact on human health. Recent research has shown a connection between indoor air pollutants, including CO_2, with health effects and academic performance (Szabados et al., 2022). According to the EPA's IAQ tools for schools (EPA, 2009), CO_2 concentrations in schools should adhere to the ASHRAE standard 62-2001 limit of 700 ppm over the outdoor concentration (just above 1000 ppm overall) for CO_2 concentrations. Besides various laws and regulations, there is a need for continuous monitoring of IAQ, which includes the installation of sensors to detect anomalous events that may have a detrimental impact on the IAQ. Sensors are generally placed on walls or ceilings to collect hourly levels of pollutants, such as CO_2, NO_2, and particulate matter (PM), which are small and aerodynamic. In addition, sensors can also collect relative humidity and temperature data. These monitoring sensors are important in the management of ventilation systems. Unfortunately, hardware sensors can encounter various issues, such as bias and precision degradation. In addition, they may experience data loss due to environmental or operability issues, which results in their measurements being unrealistic (Kim, Liu, Kim, & Yoo, 2014). When air quality is not monitored properly, it can lead to a decrease in IAQ levels. On the other hand, overestimation of the levels of pollutants can cause energy wastage. For these reasons, an effective method for early failure detection and reconstruction of faulty IAQ sensors can help increase the uptime of ventilation management.

Some investigations have used statistical methods for abnormal data reconstruction (Kasam, Lee, & Paredis, 2014; Ouyang, Zha, & Qin, 2017). Although statistical methods are easier to implement and work well when there are few abnormal data, their performance is constrained as the data complexity increases. Additionally, the majority of statistical techniques rely on linear assumptions, which are incompatible with nonlinear real-world situations. Traditional machine learning approaches can use the whole data set to understand the patterns of failure performance in order to solve this problem. Unfortunately, they require a lot of manually classified anomalies to learn a predictor from given observations (Wang, Feng, & Liu, 2021), and due to the failure of unanticipated patterns of learning, such methods have poor performance (Bu et al., 2018). The emergence of neural methods without labelled information that is capable of handling non-linear data is a major factor that has led to the increasing number of applications of deep learning in process monitoring.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Fangli Hou, Jun Ma, Jack Cheng, Helen Kwok, *Early Detection and Reconstruction of Abnormal Data Using Hybrid VAE-LSTM Framework,* pp. 933-942, DOI 10.36253/979-12-215-0289-3.93

Time series prediction using deep learning methods, especially the long short-term memory neural network (LSTM), has achieved significant achievements in recent years (X. Li et al., 2017; Qing & Niu, 2018; Su & Kuo, 2019). A hybrid convolutional neural network and long short-term memory model (CNN-LSTM) was used to impute missing values in time-series datasets for air-conditioning appliances (Hussain et al., 2022). The hybrid technique outperformed the CNN and LSTM variants in terms of performance. Ma et al. suggested a hybrid Bi-directional Imputation method using an LSTM model and Transfer Learning to fill the gaps in the energy consumption data (Ma et al., 2020). Transfer learning was utilized to prevent network saturation problems while the basic model was pre-trained on data from a comparable building. The performance demonstrated that the suggested architecture could successfully handle various scenarios with missing data, including continuous and random missing data. The developed strategy, however, was predicated on the prior assumption of source and target data collected on sufficiently similar buildings. In general, LSTMs are commonly used in a wide range of applications due to their ability to model non-linear dependencies. However, the prediction performance of LSTM can also be sensitive to the anomalies in the input due to its non-linear nature. Our proposed approach is to make sure that the input of the LSTM prediction network contains as little abnormal data as possible. Therefore, a method for abnormal detection and reconstruction in time series is necessary. However, existing abnormal detection methods require a lot of manually labelled abnormal observations. Some methods, which are based on unsupervised learning, are used for time-series abnormal detection to address these concerns by concentrating on normal patterns rather than anomalies (Breunig, Kriegel, Ng, & Sander, 2000; Cao, Nicolau, & McDermott, 2016; Erfani, Rajasegarar, Karunasekera, & Leckie, 2016). Unfortunately, due to the failure of unanticipated pattern learning, such discriminative modeling-based techniques still necessitate a significant number of normal observations and have low accuracy (Bu et al., 2018).

Traditional fault detection methods based on supervised learning require sufficient training data (D. Li, Zhou, Hu, & Spanos, 2016; Zhao, Li, Zhang, & Zhang, 2019). However, the amount of data is usually insufficient in reality, because it is difficult to get high-quality training data sets for each type of failure. Yan et al. proposed a semi-supervised fault detection method, which only uses a small amount of data to detect the failure of the air-conditioning unit (Yan, Zhong, Ji, & Huang, 2018). However, it is limited only when the same failure occurs again.

Recently, there has been a rise in deep generative modeling techniques that can be used for detecting anomalies. Autoencoder (AE) is a powerful deep learning technique that is appropriate for failure diagnosis with limited fault data since it can learn data features, avoiding the dependence on failure data (Zhang, Jiang, Zhan, & Yang, 2019). In addition, AE is a crucial tool of non-linear process monitoring as it can handle the encoding of input data and the extraction of features to provide meaningful representations of data in various applications, such as failure detection and data reconstruction. Variational autoencoder (VAE) technology has been shown to have benefits over conventional AE architecture. Both VAE and AE architectures can compress data from high-dimensional space to low-dimensional space (also known as latent space) and reconstruct complicated data. The main difference between VAE and regular AE architectures is that the former has a continuous latent space, allowing it to learn the distribution of data and reconstruct new information, which is crucial for process monitoring. However, as VAE is not a sequential model and cannot handle long-term dependencies in time series, it is possible to combine a sequential modeling approach such as LSTM models with VAE to solve this issue. Lin et al. proposed a hybrid VAE-LSTM model which can detect anomalies on multiple time scales (Lin et al., 2020). The VAE module forms local features on brief windows, while the LSTM module estimates the sequence's long-term correlation. However, if there is no abnormal data in the dataset, the hybrid VAE-LSTM model is not suitable as a means of prediction, as it will increase the computational complexity and cost. Thus, it is possible to make both the VAE-LSTM and the LSTM alone train independently and be exchanged if needed.

To effectively address the issue of sensor faults, a comprehensive framework with early fault detection and reconstruction techniques is required. However, the combination of fault data reconstruction and early failure detection is rarely reported. Previous publications have demonstrated that early failure detection has a variety of applications, including analysis of climate pattern change (Drake & Griffen, 2010; Rogers et al., 2018), credit risk diagnosis (Ali & Dağtekin, 2008; Lu, Shen, & Wei, 2013), and early failure detection of key system components (Lee, House, Park, & Kelly, 1996; Yu, Woradechjumroen, & Yu, 2014). As introduced earlier, the increasing popularity of VAE in fault detection also makes it a new approach in early fault detection. The ball screw degradation assessment method used in (Wen & Gao, 2018) is similar to the one used in the manufacturing industry. The assessment shows that the deterioration of a ball screw can be evaluated using the Variational Autoencoder Reconstruction Error (VAERE). Malfunctions in an air handling unit (AHU) were studied in (Mesa-Jiménez, Stokes, Yang, & Livina, 2021), in which the VAERE was used to reproduce the sudden change of temperature before the fault occurred. This is because VAE can model the underlying probability distribution of the input, especially when processing a time sequence with a typical periodic pattern. In the case of failure, the periodic characteristics of the time sequence will be destroyed. Therefore, the reconstruction error of the VAE can be used to observe the unusual behavior in the time series data. However, there are still issues that the existing literature does not address. Firstly, some studies adopt a reactive approach rather than a proactive approach. When a system fails, it often leads to service interruptions and necessitates engineers to temporarily shut down certain pieces of equipment in order to remedy the problem. Secondly, the probability of misjudgment of the failure diagnosis by a single indicator is high, and it is more scientifically correct to use multiple indicators for early warning. Therefore, it is necessary to develop an active multi-index method for early failure detection.

To solve the problem of sensor faults including fault detection and reconstruction, a sustainable and real-time IAQ monitoring framework is proposed, which mainly focuses on early failure detection, failure data reconstruction, and assessment of the impact of failure data on ventilation performance. Early fault detection mainly utilizes the periodic characteristics of IAQ time series data and conducts variance analysis on reconstruction errors to monitor early warning failure signals. The reconstruction model combines the VAE architecture and Long Short-Term Memory neural network (LSTM). The purpose of integrating the two structures in this study is to extract data features according to the dynamic characteristics and nonlinear dependence of IAQ data, so as to reconstruct abnormal data. The contributions of this study are described in detail as follows:

- A proactive early failure detection method is proposed for IAQ time series data. Taking advantage of the periodic and stationary fluctuation characteristics of IAQ data under normal operating conditions, the unstable behavior of the raw data before the failure is reproduced using variance analysis. The variance analysis is applied to the reconstruction error of VAE to check the fluctuation of IAQ data indicating where the failure has already occurred. Therefore, the engineers can find the potential failure and carry out maintenance, when necessary, before these failures actually happen.
- When an anomaly is detected, the reconstructed data using VAE-LSTM replaces the abnormal data. The restored data is then fed into the LSTM neural network to forecast the time series. Thus, both the hybrid VAE-LSTM and the LSTM may be learnt independently and replaced as needed. The VAE-LSTM is developed by using the normal IAQ measurement data. Given that IAQ often exhibits changing patterns over time, the time variable, Hour, is translated into one-hot encoders as conditional information. For example, the IAQ in a restaurant typically present dramatic differences during meal hours and non-meal hours, and the time variable Hour can be used to provide additional conditional information. Therefore, Hour, which can be written by one-hot encoding vectors, is supplied as an input to both the encoder and decoder to provide additional controls over the process of data generation.
- To verify the superiority of the proposed method over other neural approaches, different types of abnormal data are presented in the test dataset: the IAQ dataset is corrupted by introducing complete failure, bias failure and a precision degradation fault.

The rest of the work is organized as follows: Section 2 provides the dataset used, the method description, steps in network training and explanations of the validation performance analysis. Section 3 compares the performance of the proposed method to other methods. Section 4 discusses the conclusions and limitations.

2. MATERIAL AND METHODS

In this section, a framework for early failure detection and fault data reconstruction is designed based on VAE, as illustrated in Fig.1. Firstly, the variance analysis is applied to find the abnormal fluctuations of IAQ data before the failure occurs. Once the abnormal signal is detected, the proposed VAE-LSTM hybrid model is applied to reconstruct the abnormal data. To verify the superiority of the proposed reconstruction model, various scenarios of abnormal data are introduced into the test dataset. The remainder of this section illustrates the detailed procedures.

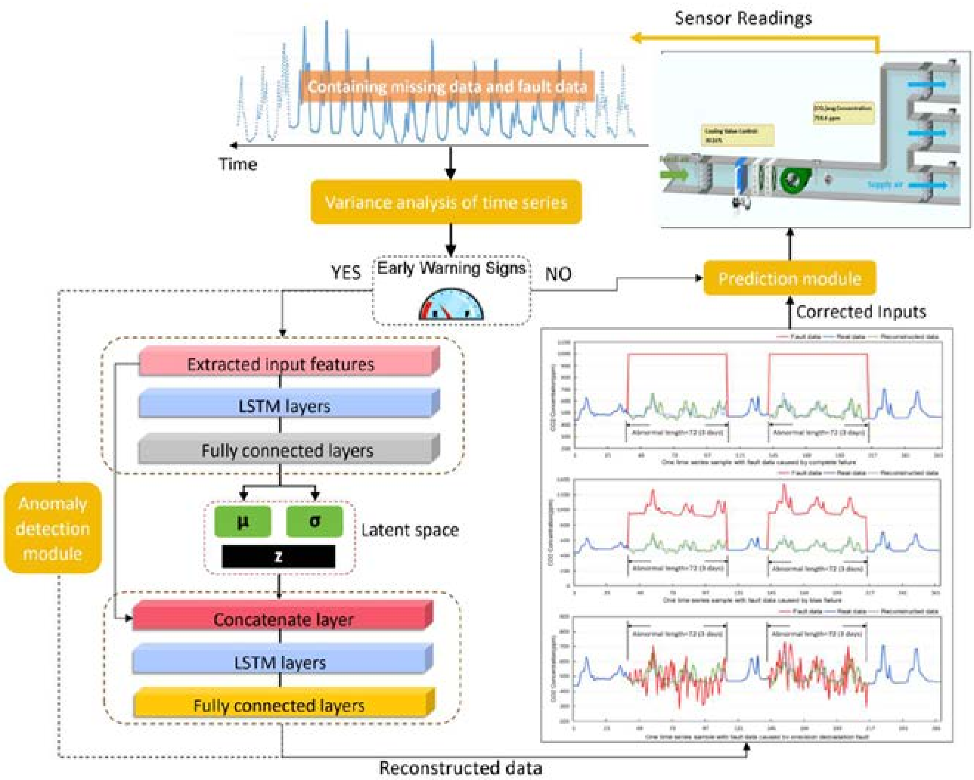

Fig. 1: Framework of this study

2.1 Data collection

The Facilities and Management Office of the Hong Kong University of Science and Technology (HKUST) provided the data used in this study. The dataset recorded IAQ data of various types of campus buildings, including canteens, library buildings, lab buildings, etc. Among them, the canteen exhibits large IAQ oscillations caused by obvious variations of pedestrian flow. Furthermore, during the peak dining hours of the canteen, pedestrian flow increases significantly, and indoor pollutants like CO_2 concentration can sometimes exceed the standard indoor concentration of 1000 ppm. This necessitates more precise ventilation management system control, and high-quality CO_2 sensor data are required for achieving this control. Therefore, we chose the CO_2 concentration of the canteen as an example to test the proposed methodology. The chosen time period included holidays, non-holidays, and the final exam period, which brings certain challenges for data analysis. In holidays, the behavior of occupants will be different from regular days, and the number of people during peak hours will be significantly reduced. These variations will affect the data patterns of indoor pollutants such as CO_2. Typical temporal models are hard to adapt, resulting in error-prone predictions. Therefore, external features need to be added to provide additional clues to the temporal model to maintain high prediction accuracy when dealing with changes in holidays and examination periods.

2.2 Early failure detection

In order to analyze the early warning signals of the sensor data generated by the ventilation management system and give the engineering maintenance personnel sufficient time to repair the failure, a fault detection technique, i.e., variance analysis, is applied to the reconstruction error of the VAE-LSTM model. The early warning indicator is applied to the time series with failures through a selected sliding window. The choice of sliding window length is a compromise between the time resolution and the clarity of transitional signal changes.

The variational autoencoder (VAE) is an algorithm for stochastic variational inference and learning using neural networks as the recognition model (Kingma & Welling, 2013). The reconstruction error of VAE can be calculated for abnormal detection. The idea underlying abnormal detection is that the VAE is not able to reconstruct unpredictable patterns or noise as well as it can regular data. Therefore, when x_i in a given time series i is reconstructed by VAE, the error between the output $\hat{x}_i$ and input of abnormal data is significantly larger. Variance is used to measure the degree of fluctuation of a set of data. Variance analysis is very straightforward to use and does not require specialized knowledge because it is a simple failure detection approach. The goal of this study is to integrate the reconstruction error based on VAE model with variance analysis to identify out-of-law abnormal fluctuations in IAQ data in advance, described as:

$$e_i = x_i - \hat{x}_i \quad (1)$$

$$\sigma_v^2 = \frac{\sum(e_i - \bar{e})^2}{n-1} \quad (2)$$

where n is the number of observations in a sample, σ_v^2 is the sample variance, e_i is the reconstruction error for each input, $\bar{e}$ is the mean value of all observations in the sample, and x_i and $\hat{x}_i$ are the actual and the reconstructed output, respectively. Therefore, the VAE indicator is derived from the reconstruction error, which is referred to as the variational autoencoder reconstruction error (VAERE).

2.3 Model development

For faulty data reconstruction and missing data imputation in ventilation control systems, a technique that can effectively handle complicated and failure data is required. This work benefits from combining the representation learning capabilities of deep generative models—in the form of variational autoencoders (VAEs)—with the temporal modeling capabilities of long short-term memory (LSTMs) to manage long-term time sequence data and generate accurate data based on intrinsic distributions. To train the proposed VAE-LSTM model without supervision, the dataset needs to be divided into a training set and a test set, with a continuous segment containing no anomalies serving as the training data and the remaining time series containing anomalies used for evaluation in the test set. Fig. 2 illustrates the architecture of the VAE-LSTM model.

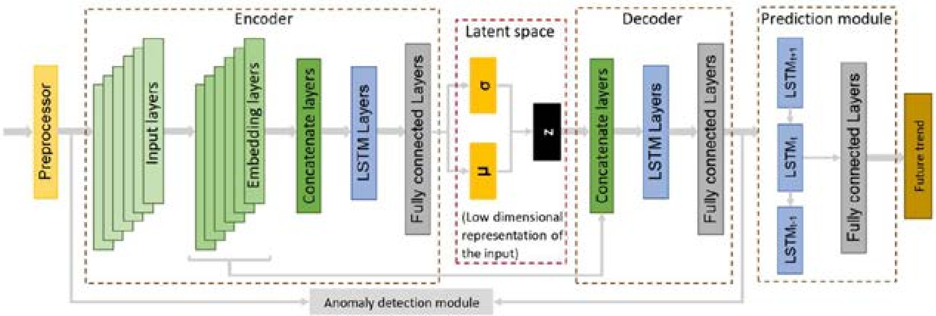

Fig. 2: The proposed VAE-LSTM architecture

The design process of the proposed model is as follows. Firstly, collect the IAQ training dataset without faulty and missing readings, and we introduce some fault data and missing intervals (with a fixed length and proportion) on the dataset to validate the model performance. In addition to sequences with faulty or missing data as the main input of the VAE-LSTM model, sequences of integers that encode the additional information provided as categorical features, such as month, weekday, hour, and holiday, serve as the second meaningful inputs. Due to the characteristics of buildings with significantly varying occupancy patterns at different hours, and to make the predictive model more concise, the variable Hour is taken as additional information for IAQ sequence reconstruction. The original IAQ data and the categorical feature which is transformed by the embedding operation are concatenated into the LSTM layer to capture the relationship between temporal features. The ReLU is selected as the activation function of the LSTM layer. The output of the LSTM goes through a dense layer with a non-linear activation function. It then generates a 2D output, just like every other encoder in a VAE architecture, which is used to approximate the mean and variance of the latent distribution. The decoder takes samples from the 2D latent distribution upsampling and then concatenates the generated sequence with the original categorical embedding sequence to provide more control over reconstructing the original IAQ sequence. LSTMs and dense layers with ReLU activations constitute the rest of the decoder structure. The training of VAE-LSTM adopts the early stopping training mechanism to minimize the combination of reconstruction loss and distribution loss. The patience was set as 10. Specifically, the training process will end if the model loss does not decrease after 10 iterations. Adam was chosen as the optimizer as it provides the best convergence (Kingma & Ba, 2014). The hyperparameters were chosen by fine-tuning the VAE-LSTM structure. The best hyperparameters were selected based on their performance in fault data reconstruction and missing data imputation.

The reconstructed sequence is utilised for time series prediction by the LSTM neural network after the abnormal data is replaced by the VAE-LSTM output. The prediction module consists of one layer of LSTM and one dense layer. Grid search is used to optimise the model architecture and hyperparameters. Input and output temporal dimensions are the same. Mean squared error (MSE) is used as the loss function throughout the training process, which was performed with 500 epochs, and the Adam optimizer with a learning rate of 0.001.

2.4 Validation scenarios

Since anomalous events are rare, it is usually not feasible to collect sufficient abnormal data for detailed characterization. Therefore, to assess the effectiveness of the proposed framework, we designed different types of abnormal scenarios with fixed lengths and proportions on the test set, with the key benefit of creating an arbitrary amount of abnormal data while using the original data as a ground truth. The downside of this procedure is that it may overfit the abnormal data or provide worse results for real anomalies. As a result, only real data is utilized to train the model, whereas anomalous data is solely used to evaluate it.

A detailed explanation of the abnormal scenarios is as follows. Anomalies such as gain and offset of sensor signals may arise due to incorrect calibration or mechanical wear over a period of time. We attempt to simulate three types of typical sensor faults: 1. Complete failure: the size is assumed to be twice the average concentration of the original data; 2. Bias failure: the size is assumed to be twice the original faulty data segment; and 3. Precision degradation fault: the size in the temporal dimension is taken as the average and standard deviation of the original data.

3. RESULTS AND DISCUSSION

We now employ the methodology described in Section 2 for the collected sensor data for analysis. Table 1 presents a statistical summary of the data in this study. Real faulty data are utilised to evaluate the effectiveness of variance analysis in early failure detection. Abnormal data scenarios are then introduced to evaluate the reconstruction and imputation performance of the proposed method against other approaches.

Table 1: The basic statistics of variables.

Attribute	Content
Variable	CO_2 concentration
Time period	From 2021/11/08 13:00 to 2022/02/19 22:00
Unit	ppm
Resolution	Hour
Mean	508.56
Minimum	412
Maximum	844.7
Standard Deviation	77.67

3.1 Early failure detection analysis in IAQ measurements

We applied variance analysis to analyze the failure of the CO_2 sensor in the indoor ventilation control system, which resulted in abnormal changes in CO_2 concentration up to 1000 ppm instantaneously. Therefore, the purpose of applying variance analysis in this study is to detect this anomaly before it occurs. Figure 3(a) shows one week of CO_2 data containing the failures, with an abnormally high CO_2 concentration.

The analysis results are shown in Figure 3, where the collected CO_2 data is presented together with the analysis results. For convenience, the variance on the Y-axis is represented on a logarithmic scale. We used different windows to obtain early failure signals, with a 14-hour window when applied to CO_2 data and a 23-hour window when applied to the reconstruction error. The choice of window size is based on the clarity of the provided signal. It is evident from the figure that the variance results for the normal data are periodic, while unexpected fluctuation patterns appear before the failure. When the variance is applied to the reconstruction error as shown in Figure 3(b), the failure signal is generated about 12 hours prior to the failure, and the reconstruction error gradually increases, which shows the unexpected fluctuation pattern before the failure. Therefore, early failure signals give time for the maintenance engineers to make the necessary adjustments and repairs before the failure actually occurs.

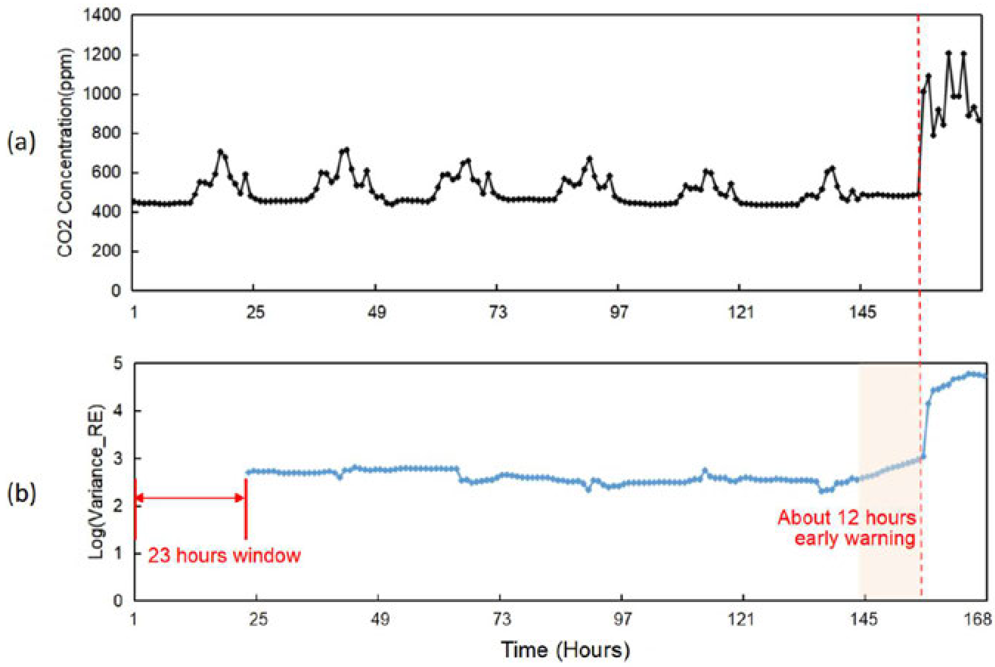

Fig. 3: Variance analysis of the CO_2 sensor failure.

3.2 Reconstruction performance of the IAQ measurements

As discussed in previous sections, three types of abnormal data scenarios are used to compare the performance of the proposed method to that of other approaches. Due to sensor ageing, damage, poor working environmental conditions, etc., a number of sensor failures may occur, with complete failure and bias failure being the most common. To evaluate the reconstruction performance of AE-based sensor faults, we introduced different kinds of faulty data in the test dataset. The magnitude size of each sensor failure is described in Section 2.4. The rate of fault data was set to 0.5, and the fault data lasting 3 days were randomly inserted into the test set. Figure 4 shows a section of CO_2 data containing fault data segments and the reconstructed results. Table 2 demonstrates the fault data reconstruction results of the AE-based model for different faulty data. Root mean square error (RMSE) and mean absolute error (MAE) are used as metrics to measure the capability of the AE-based model of reconstructing the fault data. The largest value of RMSE is 43.197 ppm calculated by the standard AE model. When the encoder and decoder structures are designed using LSTM, the reconstruction performance improves by up to 17%, which proves that LSTM can capture the nonlinear and autocorrelated relationships of CO_2 data. In addition, the reconstruction model based on VAE provides better capability for fault data reconstruction. This is because VAE can solve the problem of non-regularized latent space in the encoder and provide generation capability for the whole space. The encoder of AE produces the vectors in the latent space, while VAE outputs the distribution in the latent space for each input, adding a constraint on that distribution to convert it to a normal distribution, and this constraint guarantees that the latent space is regularized. As a result, the VAE-LSTM reconstruction accurately forces the faulty data to normality.

Table 2: Reconstruction performance of different approaches under different types of fault data.

Fault data reconstruction performance						
Reconstruction methods	Complete failure		Bias failure		Precision degradation fault	
	RMSE (ppm)	MAE (ppm)	RMSE (ppm)	MAE (ppm)	RMSE (ppm)	MAE (ppm)
AE	39.441	28.105	43.197	30.126	39.789	28.696
AE-LSTM	37.343	26.008	36.882	25.867	36.800	25.814
VAE-MLP	34.370	**24.111**	33.228	26.104	32.712	25.087
VAE-LSTM	**32.153**	24.508	**31.133**	**18.212**	**27.133**	**17.081**

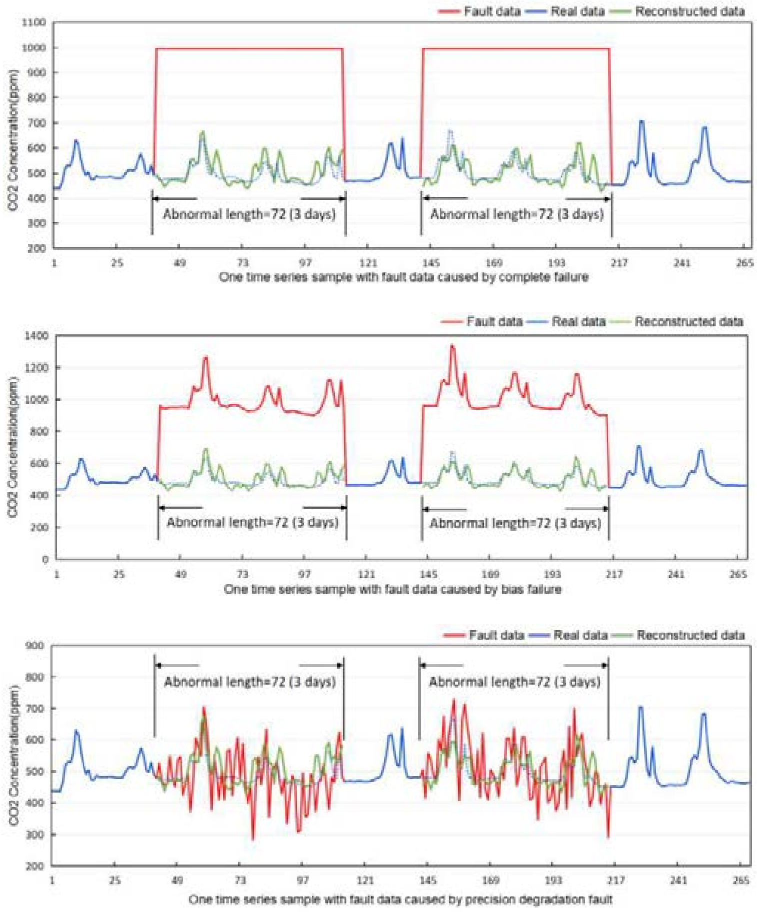

Fig. 4: Reconstruction performance of the VAE-LSTM model under interval-based fault scenarios

3.3 Discussion

This study presents a method to reconstruct IAQ data since abnormal data such as bias failure, complete failure, precision degradation fault often occur due to sensor malfunctions. One of the main contributions of this paper is the development of the VAE-based model for reconstructing various types of abnormal data, including LSTM configurations that properly depict indoor environmental patterns. The time series of CO_2 concentration, in particular, has periodic peaks and extremes, which is a complexity to consider when developing models employing LSTM. Furthermore, model training should be done offline to guarantee that the network has sufficiently learned the basic parameters in order to provide optimal learning performance for IAQ data and achieve accurate abnormal data reconstruction.

In addition to the reconstruction of indoor CO_2 data, the VAE-LSTM model developed can be generally applied to other tasks involving periodic abnormal data processing, such as indoor crowd and energy consumption. In fact, there is a link between indoor CO_2 concentration, indoor crowd, and energy consumption. CO_2 concentration can be generally used as a proxy indicator to assess whether indoor space is occupied and whether indoor crowd affects energy consumption. Our proposed VAE-LSTM approach encodes categorical features, such as months, weekdays, hours, and holidays into integer sequences as auxiliary information to capture the periodic patterns of time series data, and the original categorical sequences are connected to the generated sequences of the decoder to provide more control over the process of reconstructing and imputing the sequences. The flow pattern of a human crowd and fluctuations of energy demand have similarities with fluctuations in indoor CO_2, and both follow a cyclic pattern, so our proposed VAE-LSTM method can also be used to constitute a model for processing crowd and energy demand from abnormal data.

In contrast to other studies that only utilize VAE-based models for abnormal detection, this study incorporates variance analysis to detect non-periodic abnormal signals in IAQ data in advance, and early failure detection can prevent problems in critical parts of the Heating Ventilation and Air Conditioning (HVAC) system. For example, the case in this study is the indoor CO_2 concentrations at a university restaurant. When abnormal signals are detected using our proposed approach, the restaurant manager can contact engineers to check the system in time.

Even if part of the system facilities is shut down, the restaurant manager can prepare backup ventilating equipment in advance to ensure that the customers can enjoy their meal in a good indoor environment, especially during peak hours.

4. CONCLUSIONS

A neural approach, consisting of a variational autoencoder and long-short-term memory network (VAE-LSTM), was developed for early detection and reconstruction of malfunctioning sensors in HVAC systems in order to improve the reliability of the sensors in indoor environment control. Taking advantage of the periodicity and stable fluctuation characteristics of IAQ data, the results of variance analysis on reconstruction errors reveal that unusual behavior of the data can be detected as early as 12 hours before failure occurs. The abnormal data are then reconstructed using the developed VAE-LSTM model. The validation is carried out by introducing different types of abnormal data on the CO_2 sensor. The superiority of the VAE-LSTM was then illustrated by comparing the developed approach to other methods.

However, for an approach dealing with faulty sensors, an explanatory function of fault locations and causes should be provided to the on-site engineer in order to avoid time-consuming proactive repairs, and the knowledge-based method or expert rules can meet this requirement and capability. Therefore, in our future work, we will provide rational explanations for system failures by combining analytical-based, knowledge-based and data-driven approaches and apply them to fault detection and diagnosis of ventilation control systems, especially for large-scale building systems.

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REFLECTING USERS' PHYSICAL CHARACTERISTICS IN SPATIAL VISUALIZATION

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ABSTRACT: *This paper aims to quickly and precisely visualize remodeled design images based on image generation AI so that they can be used as alternative images in the early stages of design. In order to create a space image suitable for the user, the contents of the text are proceeded as follows. Bathrooms with many accidents in the space were selected as the target space, and users were designated as elderly people with many physical changes. Learning image data for additional training was self-generated according to the user's body characteristics, and the learning data focused on musculoskeletal aging among the body characteristics of elderly users. When the image was generated using additional training models, it was confirmed that a meaningful spatial image was created for musculoskeletal aging users, and it can be expected that the spatial image for spatial remodeling can be obtained quickly and accurately without the help of experts through subsequent studies to make it easier for general users.*

KEYWORDS: *Generative AI, Physical Characteristics, Elderly-friendly Bathroom, Detailed Modeling*

1. INTRODUCTION

This paper explores the integration of artificial intelligence (AI) technology into image generation during spatial remodeling and initial design phases. It aims to automate visualization for promoting safe space utilization by considering user's physical characteristics and to investigate various practical applications. Spatial visualization plays a crucial role in conveying design concepts and ideas visually to clients. However, generating visualizations for architectural spaces requires a significant amount of time and effort, and one alternative is to leverage image-generating artificial intelligence. By utilizing image-generating AI, detailed user input regarding spatial requirements can lead to the generation of corresponding space images.

To design safe spaces, it's essential to establish environments suitable for users and based on professional expertise, ensuring safety. However, this design process can incur costs such as labor expenses. Nonetheless, using generative AI allows for the efficient generation of trustworthy alternative space images by utilizing models trained on abundant data. Therefore, this study investigates an extended visualization approach in the field of architecture through image-generating AI. It focuses on generating a variety of personalized visualization alternatives for users, rather than presenting standardized alternatives.

2. BACKGROUND

2.1 Image Generation AI

The advancement of intelligent computing technology has brought about innovative changes in research methodologies and approaches within the field of architecture. Tools such as the architectural design assessment rule-checking system (Eastman, *et al*. 2009) and the spatial data-based building design review system (Lee, *et al*. 2012) have also been utilized. However, more recently, the rise of image-generating artificial intelligence (AI) technology has introduced significant transformations in the architectural realm. While previous studies primarily focused on the application of AI algorithms for predicting and optimizing architectural elements such as building appearance and interior composition, the present landscape is marked by image-generating AI technology providing fresh perspectives on visual representation and design in architecture. This influence extends not only to the architectural domain but also spans various other fields. For instance, within the medical sector, image-generating AI has been employed to analyze medical images and medical knowledge-based imagery (Kather, *et al*. 2022). Similarly, in the realm of arts, image-generating AI has found utility as a tool for creative artwork generation (Beyan, *et al*. 2023). This multifaceted application underscores the integration of image-generating AI across diverse domains, fostering ongoing research endeavors.

Furthermore, the focus of research has been directed towards leveraging artificial intelligence for performance optimization within the architectural context. Models powered by AI algorithms empower architects to experience energy efficiency within designs before the commencement of construction. This approach not only streamlines

Referee List (DOI: 10.36253/fup_referee_list)
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the design process but also contributes to sustainable and user-centric outcomes, fostering anticipations of substantial contributions. In essence, the amalgamation of AI technology with architecture is shaping novel research directions and enhancing both design methodologies and the conceptualization of architectural spaces.

2.2 Design of a space reflecting physical characteristics

Occupants continually modify and inhabit spaces to enhance comfort. Shifting demographics, family compositions, and evolving space roles often prompt interior modifications. Precision in incorporating users' physiological and psychological data into designs can significantly improve the quality of life by enhancing safety, usability, and independence (Demirbilek & Demirkan, 2004). For instance, designing spaces for individuals with disabilities necessitates collaboration between experts and users, ensuring their unique needs are met (Imrie, 2004). Similarly, creating spaces for children requires considerations such as play areas, noise control, and equipment tailored to their needs (Evans & Moch, 2003). Moreover, equipment scale within a space often deviates from conventional dimensions to harmonize with users' specific requirements. This departure from standardization not only influences the spatial arrangement but also distinctly shapes the manner in which objects are engaged within these environments.

Within this multifaceted framework, it becomes acutely clear that the alignment of spatial configurations and amenities with the diverse physiological attributes of users is an imperative. This thematic focus is central to the present study, which delves into the meticulous curation of spatial layouts and equipment, meticulously calibrated to resonate with the myriad physiological attributes presented by users. This comprehensive endeavor stands as the foundation for establishing environments centered around the user, thus aiding in improving the overall quality of life.

3. AI-BASED SPATIAL IMAGE GENERATION

3.1 AI-Based Image Generation Test

To enhance satisfaction and facilitate convenient usage of spaces, appropriate improvements are essential. To achieve these improvements, a clear understanding of the users of the space is crucial. Furthermore, it is necessary to incorporate the layout and facilities of the space based on the users' physical characteristics. To generate spatial images based on these physical characteristics and reflect the users' desired points of improvement, a focused test was conducted. We tested image generation using the text-to-image functionality of the AI platform named Stable Diffusion (SD), which utilizes a Diffusion model. This involves using a deep learning model to generate images based on natural language input (Zhang, *et al*. 2023). In order to utilize SD, relevant prompts need to be formulated for the desired images. These prompts are categorized into Positive Prompts and Negative Prompts. Positive Prompts are crafted to enhance space types and image quality, while Negative Prompts are designed to prevent image degradation or errors. The image generation test focused on residential bathroom spaces, which often experience numerous accidents. In this test, not only were typical bathroom images in Korea generated, but also images tailored to the physical characteristics of elderly users, in an effort to ascertain if these factors were being considered. For this purpose, the generation of bathroom images was performed using image generation AI, with specific attention to bathrooms in domestic settings, particularly bathrooms prone to accidents. To ensure the consideration of users' physical characteristics, bathroom images that catered to the needs and safety of elderly individuals were generated alongside conventional bathroom images.

Table 1 Generating images by text

Standard bathroom	
Positive prompt	A basic bathroom with a white porcelain toilet, a sink with a chrome faucet, and a standard bathtub with a showerhead. The walls are tiled with white rectangular tiles and the floor is covered with grey linoleum, Simple, clean, functional, standard, basic, minimalistic, bright lighting, plain, High resolution, sharp focus, realistic lighting, standard aspect ratio.
Negative prompt	Multiple layouts, avoid bright and clean elements, low quality, bad proportion, normal quality, watermark, bad perspective, confusing details, text, blurry

Musculoskeletal aging user bathroom	
Positive prompt	Musculoskeletal Aging, bathroom for the elderly, wall handrail attached, non-slip tile, perspective view, wide angle, Simple, clean, functional, standard, basic, minimalistic, bright lighting, plain, High resolution, sharp focus, realistic lighting, standard aspect ratio, standard.
Negative prompt	Multiple layouts, avoid bright and clean elements, low quality, bad proportion, normal quality, watermark, bad perspective, confusing details, text, blurry

3.2 Physical Characteristics-Based Training for Spatial Image Generation

Upon reviewing the generated images, it is evident that the spatial visualization capability is impressive; however, images are being generated without considering user conditions, required expertise, and specific situations. Observing the Korean-style bathroom images, the structure of a typical Korean apartment bathroom, including the sequence of toilet, sink, and shower booth/bathtub, is not reflected in the generated images. Instead, the images are generated with a focus on a single bathroom component, neglecting the holistic bathroom layout. In the case of elderly friendly bathroom images for older users, safety facilities should be reflected to prevent accidents when the elderly use the space. However, the generated image does not reflect the safety equipment properly, or, even if installed, the safety equipment is attached to a space other than the bathroom, generating a facility that is unsuitable for space conditions. Consequently, to utilize image-generating AI for generating

Elderly-friendly bathroom space images, an approach involving the addition of learned images that incorporate safety equipment in appropriate positions within the bathroom based on medical expertise and the physical characteristics of the elderly is required.

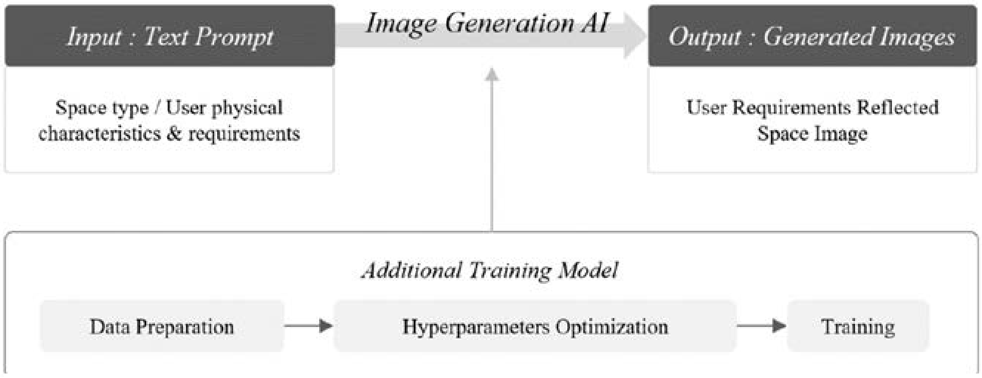


Figure 1 Summary of the configuration outlined in this study.

4. ADDITIONAL TRAINING FOR DESIGN COMPONENTS VISUALIZATION

4.1 Data preparation and Pre-processing

The datasets required for further training should comprise image files along with corresponding text descriptions. However, the available training images for Korean-style bathroom structures, obtainable from the current website, predominantly consist of wide-angle images to capture confined bathroom spaces. Consequently, even with additional training, the generated images might continue to emphasize wide angles or exhibit pronounced distortion. Furthermore, when considering bathrooms designed for elderly users, images depicting safety equipment installed by non-experts without professional knowledge outnumber those accounting for individualized physical characteristics. This discrepancy could potentially result in compromised safety and reliability. Therefore, the generation of image data conducive to effective learning is imperative.

Given this scenario, it becomes essential to independently generate image data specifically tailored to bathrooms for the elderly, considering their unique physical attributes. To accomplish this, a comprehensive exploration of

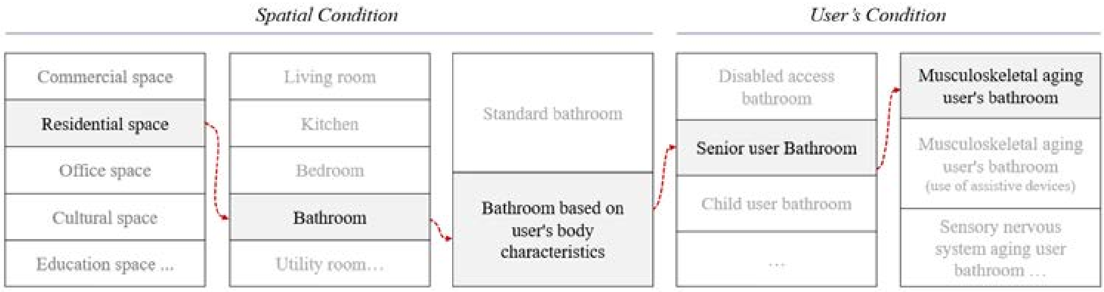


Figure 2 Scope of Work

bathroom layouts, incorporating safety equipment based on the aging characteristics of the elderly, is crucial. Additionally, the collection of fundamental components necessary for spatial Building Information Modeling (BIM) is paramount. In this paper, we have developed an additional training model that centers around musculoskeletal aging, a facet of the aging process significantly influenced by environmental factors and exerting significant effects. To ensure the safe use of the bathroom, safety equipment that can be installed includes bathroom grab bars, floor mats, shower chairs, and more(Gitlin, *et al*. 1999)(Aminzadeh, *et al*. 2000).

Table 2 Information about Properties of BIM Objects

N	*Bathroom facilities*	*Height (mm)*	*Width (mm)*	*Depth (mm)*	*N*	*Bathroom facilities*	*Height (mm)*	*Width (mm)*	*Depth (mm)*
1	A washbasin with a wide top	120	750	470	6	Walk-in bathtub	780	1150	930
2	Toilet wall grab bar	304	685	50	7	Draw-out faucet	220	505	273
3	Washbasin with chair	750	595	455	8	Folding shower chair	424	-	604
4	Nonslip floor	-	-	12.7	9	Bathtub/shower grab bar	889	482	50
5	Toilet side grab bar	300	100	738	10	Shower curtain	1803	107	80

<Table 2> represents a list of BIM objects for bathroom safety equipment collected for the purpose of BIM modeling. This list is a compilation of objects sourced either from the bimobject website, which offers downloadable objects for 3D modeling, or generated directly. The collected objects are categorized based on users' physical characteristic, bathroom areas, and expected effects. This categorization serves as the foundation for crafting content in the training text, enabling the generation of images in accordance with prompts entered by users during the image generation process. The contextual text concerning bathroom areas and anticipated effects will be utilized in the future for the individualized training of each object when they are added separately to the model.

Table 3 Categorization of Safety Facilities

Classification criteria		Bathroom facility BIM object									
		1	2	3	4	5	6	7	8	9	10
Aging characteristics	A-1. MA	●	●	●	●	●	●	●	●	●	●
Expectation effectiveness	B-1 Anti-slip				●						●
	B-2 Maintaining body temperature										●
	B-3 Smooth movement						●	●			
	B-4 Supporting device	●	●	●		●			●	●	
	B-5 Emergency call facility										
Bathroom area	C-1 Basin	●		●							
	C-2 Toilet		●			●					
	C-3 Bathtub						●	●			
	C-3 Shower booth								●	●	●
	C-4 Floor				●						
	C-5 Ceiling										
	C-6 Wall										

4.2 Additional Training

To facilitate further learning, a dataset for additional training model is established by modeling safety-equipped bathrooms suitable for each stage of aging that was previously generated<Figure 3>. This dataset encompasses

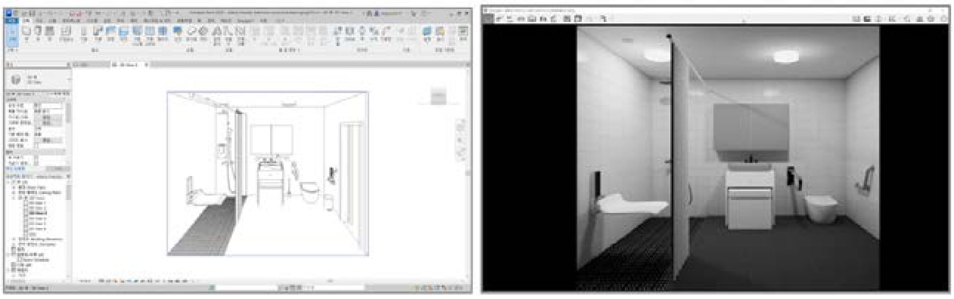


Figure 3 3D Space Modeling and Rendering

training image data sets and individual text files (.txt) associated with each image. These efforts are aimed at constructing a dataset for generating additional training models.

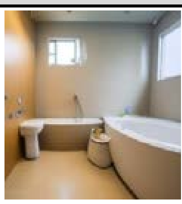
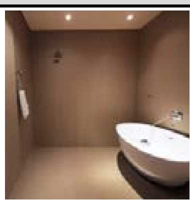
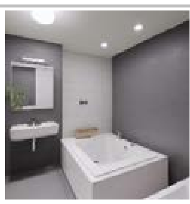
The generation of text files is facilitated through the utilization of BLIP Captioning within the Koha_ss GUI, an option found under Utilities. BLIP Captioning enables the individual generation of text files for a substantial number of images. For the task of further training, a LoRA model is generated employing Dreambooth-based LoRA GUI, Kohya_ss. LoRA, denoting Low-Rank Adaptation, effectively trains on high-quality images. The training settings for Dreambooth LoRA include parameters such as Train batch size: 1, Epoch: 120, Learning rate: 0.0001, Learning rate scheduler: cosine, and Learning rate warmup: 10. The model employs the Stable-Diffusion-v1.5 as a pre-trained model. The training environment was executed on a PC equipped with an RTX A6000 GPU model. Utilizing prepared training data, the model generation results in a .safetensors formatted model file of size 144MB.

5. EVALUATION OF ADDITIONAL TRAINING MODELS

5.1 Evaluating Enhanced Model Performance

The manipulation of model weights in its application allows for varying degrees of reflection in the generated images. When prompts are entered, the LoRA augmented model, along with its associated weight, can be specified for incorporation, as illustrated in <Table 4> presenting the test images. The weight values, ranging from low 0 to high 1, facilitate a continuum of image representation. A weight value of 0 corresponds to an image where the model has not been applied, thus lacking the reflection of Korean-style bathroom structures and characteristics. Conversely, as the weight approaches 1, a gradual integration of Korean-style bathroom imagery becomes apparent.

Table 4 Generated image result according to model weight

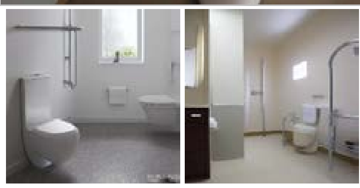
Weight	Generated Images				
0.0					
0.3					

0.7	

5.2 Utilization Scenarios of the Additional Training Model

For the purpose of generating bathroom spatial design images based on physical characteristics, further training was conducted specifically focusing on age-related musculoskeletal changes. In the context of this study, a comparative analysis is carried out between images generated using the trained model and images generated without the utilization of the model. The intent is to contrast the images produced by the model-based approach with those produced independently, as illustrated in the table below.

Table 5 Comparing images for elderly users' bathrooms with/without extra models.

		Case A	Case B
Design Requirement	Space	Bathroom (Residential Space)	
	User physical characteristics	Musculoskeletal aging user	
INPUT	Model	N/A	Musculoskeletal aging user bathroom (.safetensor)
	Positive prompt	AIP_Elderly-friendly bathroom, Musculoskeletal aging, senior-friendly, senior housing, safety, fall prevention, bathroom, restroom, elderly, senior citizens, elderly users over 70, supporting device, device for safe toilet use, nonslip tile, toilet wall grab bar, toilet side grab bar, shower curtain, basin chair, folding chair	
	Negative prompt	Bad quality, duplicate, blurry, bad proportions, confusing details	
OUTPUT	Generated image		
		 …	 …

Overall, when comparing the generated images of Case A, which were produced without utilizing the augmented training model, with the images of Case B generated using the augmented training model, it becomes evident that Case A exhibits inaccuracies in the positioning and forms of the attached fixtures. Conversely, for Case B, where the augmented training model was employed, no errors are observed in the placement and forms of the safety equipment.

6. CONCLUSION

In conclusion, this paper explores the integration of AI in spatial remodeling and initial design stages with a focus on generating spatial images that reflect user physical characteristics. The objective is to provide users with safe spatial images, taking into consideration the user's physical attributes and real-world usage within the space.

Therefore, this paper targets the bathroom space and selects elderly individuals as the space users, aiming to generate safe bathroom images for seniors experiencing physical characteristics related to musculoskeletal aging through additional model training.

To facilitate additional training, suitable safety equipment for the user's physical aging characteristics was investigated, and high-quality training data were constructed by generating image data independently. Corresponding training text files were created for each image to ensure specific training for the images. As a result, it was observed that the images generated using the additional training model had fewer errors related to safety equipment compared to using the existing model, and suitable safety equipment was placed within the space, demonstrating a different outcome. This cost-effective approach recognizes the potential of AI in the field of spatial design, prioritizes a user-centric approach at the intersection of AI and architectural design, and advances and improves the design process. In addition to musculoskeletal aging, which was the focus of selecting elderly individuals as the target for additional training model creation in this paper, a comprehensive examination of aging occurring in various body structures or the selection of a more diverse range of subjects can expand the scope and target of additional training. Beyond simple visualization, this enables detailed spatial visualization based on user requirements through text input for image generation, which can be expected to be utilized in various fields for AI-generated images.

7. ACKNOWLEDGMENTS

This research was supported by Basic Science Research Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Education (Grant NRF-2022S1A5A2A03053998)

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GEN AI AND INTERIOR DESIGN REPRESENTATION: APPLYING DESIGN STYLES USING FINE-TUNED MODELS

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ABSTRACT: *This paper explores the applicability of Image-generation AI in the field of interior architectural design, with a particular focus on automating interior design representation based on design styles. Interior design representation involves a complex process that integrates visual elements with functionality and user experience. Effectively visualizing this process is essential for facilitating communication among the various stakeholders involved in the design process. However, traditional visualization methods are constrained by expert resources, costs, and time limitations. In contrast, image-generation AI has the potential to automate various design elements, including design styles, components, and spatial arrangements, to enhance representation. In this study, we evaluated the performance of a base model using various design styles and, based on the evaluation results, selected styles for fine-tuning. The methodology for fine-tuning these design styles involved the following steps: 1) data preparation and preprocessing, 2) hyperparameter optimization, and 3) model training and construction. Utilizing the fine-tuned model thus constructed, we conducted image generation demonstrations. The research results revealed that design styles not well represented by the base model were effectively captured, and high-quality images were generated by the fine-tuned model. Notably, this fine-tuned model demonstrated the ability to represent images of specific design styles with a high degree of accuracy in capturing the characteristics and keywords associated with each style, compared to the base model. This implies that through fine-tuning image-generation AI, a wide range of applications can be inferred when aiming to create customized designs by considering these aspects. In conclusion, this study explores an efficient approach to interior design representation in the field of interior architecture by employing image-generation AI and proposes a method to effectively generate visualized images by training on design style keywords. Through this approach, our study can contribute to improving the interior design process by facilitating the generation of visualized images that reflect design styles. Furthermore, the study aims to suggest the potential for applying this approach not only to the field of interior architecture but also across various domains to achieve effective visualization.*

KEYWORDS: *Interior Architecture Design, Interior Design Representation, Generative AI, Model Fine-tuning*

1. INTRODUCTION

Interior design representation plays a crucial role in the field of interior architecture, effectively conveying ideas and designs through visual media and facilitating effective communication among various stakeholders involved in the design process (Chiu, 1995). In interior spaces, design styles signify the approach and method of planning and decorating a space, shaping and emphasizing the aesthetic, functional, and psychological aspects of the space. Design styles encompass a variety of preferences and trends influenced by the users and purposes of the space, impacting choices in color, patterns, materials, furniture, and accessories (Goldschmidt et al., 1998; Eckert et al., 2000). Additionally, they serve as a means to reflect individual identity and lifestyle, reflecting personal preferences and tastes.

Therefore, understanding and proposing customized designs that consider user preferences in the spatial visualization process is essential. However, this process necessitates expertise to comprehend the diverse preferences and requirements of users, as well as the desired design styles and spatial elements for visualization. This requires a significant investment of time, cost, and effort for both experts and non-experts (Lee et al., 2020).

Recent advancements in deep learning technology have sparked significant interest in generative artificial intelligence (Gen AI). As a result, various research endeavors are underway in the realm of visual content creation using image-generation AI (Image-Gen AI) based on large language models (LLMs). Expanding upon this trend, our study aims to propose an approach for automating interior design representation using Image-Gen AI. This

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Hyun Jeong, Youngchae Kim, Youngjin Yoo, Seunghyun Cha, Jin-kook Lee, *Gen AI and Interior Design Representation: Applying Design Styles Using Fine-Tuned Models,* pp. 950-957, DOI 10.36253/979-12-215-0289-3.95

approach allows for the generation of diverse design visualization alternatives based on user preferences and objectives, all without the need for specialized expertise.

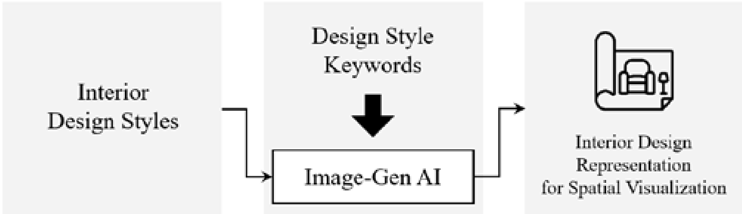


Fig 1: An Overview of the Study

2. BACKGROUND

2.1 Deep Learning-based Image-Gen AI

Image-Gen AI is based on deep learning and is a versatile technology applicable in various fields, including natural language understanding, computer vision, image processing, data generation, prediction, and more (Liu et al., 2021) This technology is used to generate new image content or outputs based on given data or information. To accomplish this, Image-Gen AI is pre-trained on large datasets and then fine-tuned for specific targets. During the training phase, Image-Gen AI learns features and patterns from the data, and in the generation phase, it uses this learned information to generate new image data. This process can be considered an example of transfer learning, allowing effective generation results even with limited data. Image-Gen AI can be trained to incorporate additional conditions such as image type, style, color, and more, enabling it to generate images that meet specific criteria. This reduces the need for extensive training on the target while enabling various applications like style transformation, ensuring similarity between images, image synthesis, and more (Nichol et al., 2021).

For these reasons, recent applied research efforts are being conducted in the field of visual content creation using a variety of Image-Gen AI models such as Midjourney (Oppenlaender, 2022), DALL-E 2 (Ramesh et al., 2022), Stable Diffusion, and others (Ramesh et al., 2022; Saharia et al., 2022; Rombach et al., 2022; Oppenlaender, 2022). While research using Image-Gen AI has been extensive, it remains limited in the field of interior architecture. Therefore, in this study, we aim to explore an approach to fine-tune Image-Gen AI models based on design styles and implement a model for the automatic visualization of interior design representation.

2.2 Potential for Automating Interior Design Representation through Image-Gen AI

In the field of interior architecture, the evolution of deep learning technology is reshaping the way spaces are conceptualized and realized. In the past, designers relied on manual sketches and 2D drawings to convey ideas for spatial visualization reflecting interior design representation (Ching, 2011). However, with the emergence of advanced technology and computer-aided tools, spatial visualization has undergone a paradigm shift (Karras et al., 2018). The integration of sophisticated software, computer-aided design, and 3D modeling tools has empowered designers to visualize spaces realistically and immersively. Thanks to these advancements, designers can accurately represent intricate details such as lighting, materials, textures, and shadows, not just the physical layout. As a result, stakeholders, including clients and project collaborators, can experience the proposed design in a lifelike manner before actual construction commences (Ah-soon & Tombre, 1997; Oxman, 2006).

With the continuous advancement of deep learning technology, Image-Gen AI can effectively generate images that match the intended target by fine-tuning a base model pretrained on large datasets. Leveraging these characteristics of Image-Gen AI, it is possible to implement an interior design representation model based on specific design keywords, fine-tuning it to reflect the desired design style. This model can be utilized as a tool to generate a variety of design alternatives that users desire during the design process and enhance the decision-making process (Jeong & Lee, 2023). Therefore, in this study, we aim to conduct fine-tuning of design styles on Image-Gen AI and explore methods for automating interior design representation.

3. MODEL FINE-TUNING FOR INTERIOR DESIGN REPRESENTATION

3.1 Overall Process

In this study, the image generation performance of three major AI platforms in the Image-Gen AI field, Stable Diffusion, DALL-E 2, and Midjourney, was examined and compared. First, these Image-Gen AI platforms employ two main methods: text-to-image (Txt2img) and image-to-image (Img2img). Each of these platforms has unique and distinctive image generation capabilities, along with their specific technical attributes, strengths, and limitations.

DALL-E 2, trained on a large-scale image dataset, demonstrates exceptional abilities in generating detailed and complex images. However, due to its complexity and resource-intensive nature, it may have longer processing times, and its dependency on text prompts might result in shortcomings in image stability and consistency. Midjourney excels in generating images inspired by specific visual styles or artistic aesthetics. However, its emphasis on artistic expression may result in relatively less accurate representation of real objects or scenes. Stable Diffusion prioritizes stability and accuracy in image generation. It is based on LLMs and provided as an open-source platform, making it user-friendly for customization. The transparency of the source code allows users to understand, modify, and apply the underlying algorithms, enabling them to verify, align with their intended purposes, and enhance image generation results.

Each platform has its unique strengths and specific limitations. Considering these factors, this study utilized Stable Diffusion, which demonstrated the most outstanding performance in terms of image generation stability, accuracy, and the ability to cater to specific requirements through open-source access. The research methodology, rooted in the utilization of Stable Diffusion, is structured into three primary phases. Step 1: Testing image generation via text descriptions for design styles, Step 2: Model Fine-tuning, Step 3: Evaluation of Fine-tuned Models. The schematic representation of the entire process outlined in this section is depicted in Fig 2 below.

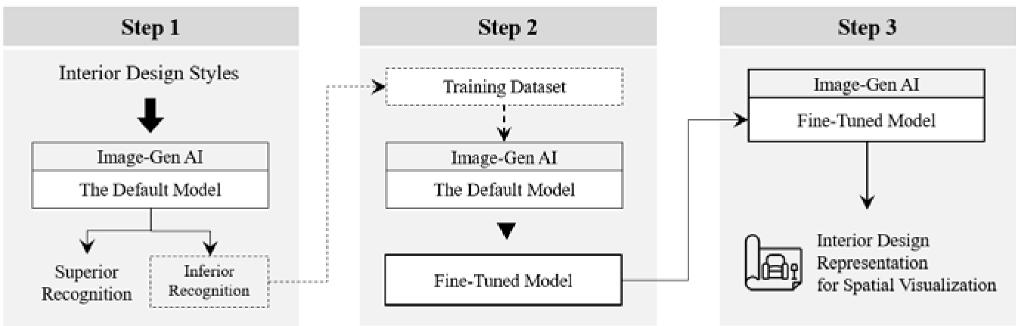


Fig 2: The Process of Model Fine-tuning

3.2 Step 1: Testing Image Generation via Text Descriptions for Design Styles

In this section, we conduct tests to evaluate the performance of the Image-Gen AI model for various interior design styles. Our study focuses on the text-to-image (txt2img) approach, generating images based on text descriptions. To prevent the Image-Gen AI model from inferring styles solely from text descriptions, we perform prompt engineering adhering to guidelines. This prompt consists of two key components: 1) prompts for the target design style, and 2) prompts for image quality. Additionally, we categorize positive and negative aspects that encompass both reflective and non-reflective elements of the generated images.

The image generation process utilized the DPM+2M Karras sampler along with the widely used open-source model, SD1.5V checkpoint (v1-5-pruned.ckpt). Essential configurations, including sampling steps and CFG scales, were set to default values, and the image size was defined as 1024x512 pixels. Each image generation took an average processing time of approximately 5 seconds. Table 1 below illustrates the configuration settings employed in the image generation process, and Table 2 showcases the standard format of the text prompts utilized for image generation.

Based on the preceding discussion of the image generation process, we conducted an evaluation of the recognition level for interior design styles using the generated images. Table 3 below provides outcomes of the generated images based on their recognition levels. The base model of Stable Diffusion demonstrated a stable generation capability for high-quality images across most styles. However, its expressive capacity was relatively limited in terms of being recognized as specific design styles, particularly due to lower comprehension of certain styles. To address these constraints and enhance image generation accuracy, we deduce that fine-tuning for specific targets is imperative.

Table 1: Configuration Settings for Image Generation

GPU	Base model	Sampling Method	Sampling steps	CFG Scale	Resolution
A6000 47.5 VRAM	SD v1.5 ckpt	DPM+ 2M Karras	25	13	1024×512 (2:1)

Table 2: The Standard Format of Prompts Used for Image Generation

Prompts	Positive	Negative
Design Style	Design Style interior, Space zoning	*None*
Image Quality	Professional photograph, photorealistic rendering, realistic, enhance-detail, v ray rendering, full HD, masterpiece, highly detailed, high quality, 8k, full shot, deep depth of field, f/22, 35mm	Bad proportion, Low quality, awkward shadows, unrealistic lighting, pixelated textures, Worst, noisy, unrealistic reflections, normal quality, watermark

Table 3: Sample Results of Generated Images based on Recognition Levels

Recognition Level	Superior	Inferior
Image-Gen AI based generated Images	 "*Industrial* Style Interior, A living room"	 "*Brutalism* Style Interior, A living room"

3.3 Step 2: Model Fine-Tuning for Design Styles

In this section, the process of fine-tuning the model for the target design style (ex. Brutalism) encompasses three key steps: 1) Data Preparation, 2) Hyperparameter Optimization, and 3) Training.

Firstly, in the Data Preparation step, we focused on the collection and preprocessing of data tailored to the specific target design style. This Training Dataset requires two primary components: Image Data and Text Data. Table 4 provides an example of the training dataset.

Table 4: An example of the training dataset / ***content*** (*e.g.*, a space), ***style*** (*e.g.*, a design style) and *scene description*.

Image Data	Text Data
	"A ***Brutalism style*** interior in a ***Living room*** *with sharp lines that exemplify the brutalist aesthetics. Featuring shades of grey, concrete, and metallic tones, it showcases a minimalist living room characterized by grey hues and a monochrome color scheme."*

The subsequent stage involved the optimization of the model's hyperparameters to elevate its image generation performance for the specified design styles. This process encompassed the refinement of parameters like learning rate, batch size, and network architecture to attain improved outcomes. Table 5 presents the hyperparameters employed during the model fine-tuning.

Table 1: Optimized Hyperparameters for Model Fine-tuning

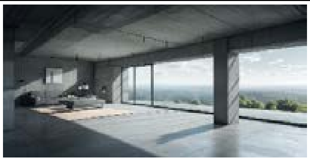
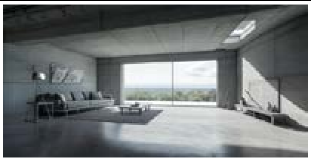
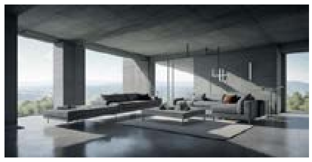
Training data	Epoch (Training steps)	Batch size to train	Learning rate	Learning rate Scheduler	Learning rate warmup
15	100	1	0.0001	Constant	10

The ultimate training phase involved the model being subjected to training using the meticulously prepared dataset and meticulously optimized hyperparameters. The process of model fine-tuning was executed using the training dataset and specified hyperparameter configurations to create the target model. The training duration amounted to approximately 25 minutes. Through this training, the model was tasked with comprehending the distinct attributes and intricacies of the designated design style, consequently empowering it to craft images that exhibit a heightened alignment with the intended aesthetic. This fine-tuned model is utilized in conjunction with the default model during subsequent image generation endeavors.

3.4 Step 3: Evaluation of Fine-tuned Models

Through the subsequent fine-tuning process, the model learned from both image and text data related to design styles that initially exhibited inferior recognition. As a result, it was enhanced to effectively depict the distinctive characteristics of the trained design styles, showcasing a heightened ability to generate high-quality images. Table 6 below illustrates the results of image generation based on the application or absence of the fine-tuned model. This highlights the tangible impact and comparison of interior design style image generation that was not achievable before the model's fine-tuning adjustments. Additionally, the weights of the model parameters correspond to finer adjustments made to the model, reflecting a more distinct influence on the image generation process.

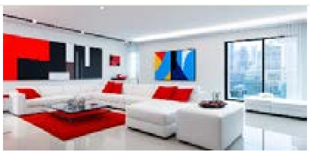
Table 6: Qualitative Comparison of Image Generation: Impact of Applying Fine-Tuned Model

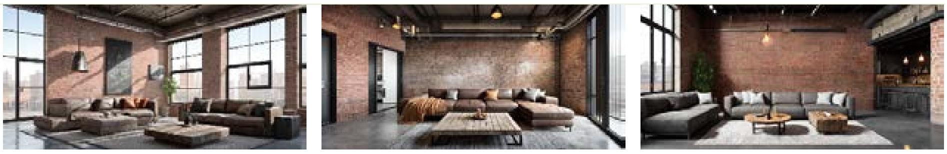
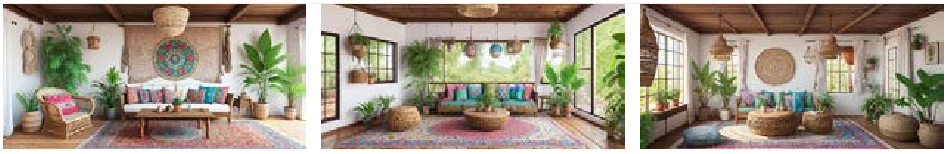
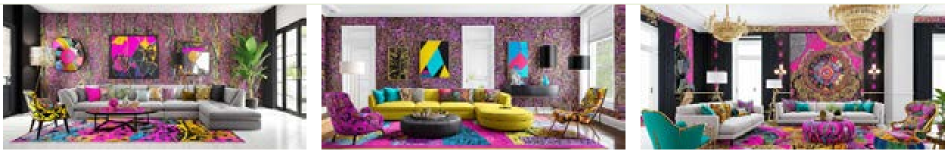
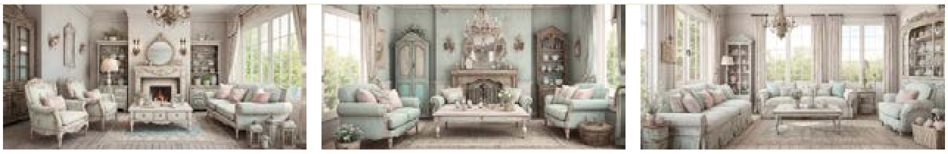
Weight of Fine-Tuned Model	at W 30%	at W 60%	at W 90%
Image-Gen AI based generated Images			
	"*Brutalism* Style Interior, A living room"		

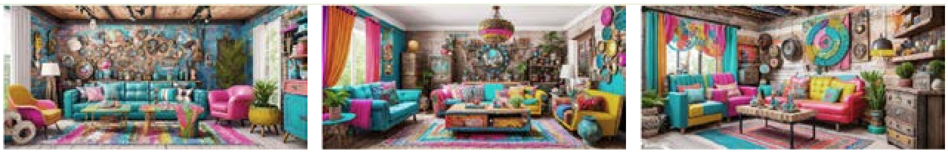
4. DEMONSTRATION

In this study, based on the procedures outlined in the previous Section 3, a demonstration was conducted using Image-Gen AI to generate images of more than 15 interior design styles. The target space was limited to residential living rooms. The generated image results for each design style are presented in Table 7, encompassing both the default model and the fine-tuned model for image generation. This demonstration facilitates practical comparisons in the interior space visualization process through the generation of design alternatives, as proposed in this study. Additionally, it allows for the observation of the potential for learning various customized design styles.

Table 7: Image Generation using Default and Fine-Tuned Models

Design Style	AI-based generated Images		
Modern			
Contemporary			

Industrial	
Scandinavian	
Bohemian	
Rustic	
Hygge	
Maximalist	
Shabby	
Provence	
Art Nouveau	
Oriental	
Colonial	
Zen	

Junk	

5. CONCLUSION

In this study, we investigated a method for fine-tuning design styles using Image-Gen AI and automatically generating spatial images reflecting interior design representation. During the research process, we conducted an evaluation of the recognition level for interior design styles by the base model. We implemented a design style visualization model based on detailed keywords for the Brutalism style, which was chosen as one of the fine-tuning targets. The model effectively learned the characteristics of the style and demonstrated the ability to intricately represent the visual attributes of the style.

Through comparative analysis with the base model, we confirmed the high likelihood of visualizing the features of the style, thus validating the capability to effectively visualize spaces that align with user preferences through additional fine-tuning for interior design styles. Furthermore, this research approach showcases the potential for Image-Gen AI to be utilized in various fields, and we aim to suggest its applicability in future research and application domains.

6. ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MIST) (No. NRF-2021R1A4A1032306)

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EARLY VISUALIZATION APPROACH TO THE GENERATIVE ARCHITECTURAL SIMULATION USING LIGHT ANALYSIS IMAGES

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ABSTRACT: *This paper presents the potential utility of generative artificial intelligence-based light analysis simulation visualization image in the early phase of architectural planning and design. Facilitating the simulation of a building's performance during the early stages of planning and design presents numerous advantages, such as cost savings and enhanced ease of communication among stakeholders. However, the assessment of design performance is typically conducted during the design development phase or post-design completion. Processing a substantial volume of data based on design alternatives demands considerable time and resources, thus constraining the immediate provision of simulation results. This paper aims to utilize generative AI to produce visualization results of simulations with a predefined level of accuracy, with a specific focus on the architectural aspect rather than the physical and engineering functionalities of the simulation. Consequently, the study employs the following approach: 1) Analyze prominent characteristics and elements within light analysis simulation. 2) Based on this analysis, generate high-quality visualization image data additionally through Building Information Modeling (BIM). 3) Construct a dataset by pairing the generated lighting analysis visualization image with prompts. 4) Utilize the established dataset to create an additional learning model for light analysis visualization images. This study is expected to provide immediate and efficient assistance in design decision-making during the early phases by generating visualization images with high accuracy, reflecting prominent qualitative aspects related to light analysis and processing within the simulation.*

KEYWORDS: *Architectural Design, Architectural Visualization, Generative AI, BIM (building information modeling), Fine Tuning Model*

1. INTRODUCTION

This study aims to utilize generative artificial intelligence (AI) to create and employ light analysis visualization images within architectural spaces. The current simulation methods quantitatively derive predictive outcomes based on physically designed environmental conditions, which are then visualized. However, as the number of design alternatives increases, processing extensive data incurs time and cost, posing a limitation, particularly in promptly delivering results during the design phase. In the initial design stages, swift generation and evaluation of various design alternatives are vital to meet given requirements. During this process, offering intuitive visualization results rapidly proves more effective than ensuring the precision of simulation outcomes. Therefore, this research is conducted with a primary focus on architectural visualization, which aids in the early design phase, rather than solely relying on physical and engineering-based imagery. In the initial design phase, the precision of the design model is diminished due to the uncertainty of design conditions. However, the utilization of this technology enables straightforward assessment of visual performance aspects, such as a building's energy efficiency and lighting environment, even at the conceptual model level. Particularly, these visualizations serve as effective tools for comparing and evaluating various design alternatives, fostering communication among stakeholders.

Building upon this foundation, a test of the potential for light analysis visualization images in architectural spaces is conducted using image-generating AI. However, the generated images lack reflection of the elements and characteristics of light analysis visualization within spaces, thus clearly indicating the need for further refinement through additional training. For the purpose of generating light analysis images using AI, a process involving '1) Setting the Scope of Light Analysis, 2) Data Preparation, and 3) Training' is carried out. Representative elements of general characteristics from light analysis images are chosen to define the range of training data generation. Model construction employs a diffusion-based model implemented based on the Large Language Model (LLM) for additional training, and hyperparameters are adjusted to ensure the generation of high-resolution images. The constructed supplementary training model is demonstrated in real-world applications of image-generating AI, such as the creation of light analysis visualization images based on different time periods.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Bomin Kim, Sumin Chae, Youngjin Yoo, Jin-Kook Lee, *Early Visualization Approach to the Generative Architectural Simulation Using Light Analysis Images*, pp. 958-964, DOI 10.36253/979-12-215-0289-3.96

2. BACKGROUNDS

2.1 Image Generation Artificial Intelligence (AI)

The recently emerged generative AI paradigm has entered its preliminary stages, yet it wields substantial influence across diverse industrial sectors. It is anticipated that with ongoing technological advancements, this nascent field will expand the horizons of innovation [Mackinsey, 2023]. Image generative AI such as Stable Diffusion and DALL-E have instigated substantial transformations akin to sectors beyond, including art and entertainment, within the domain of architectural design as well. However, the latent potential within the realm of architectural design visualization remains notably underdeveloped.

This study aims to propose a novel approach to architectural design visualization through the utilization of image generative AI models. Architectural design methodologies intertwined with AI offer a departure from conventional design practices that have traditionally relied upon designers' creativity and expertise to address multifaceted requirements. By systematizing the data generated and incorporated during the design and construction processes through automated tools, the objective is to assist in resolving ambiguities, risks, and other issues that might arise in human-executed tasks by architects, contractors, and related stakeholders.

Given the advancements in LLM models and image generation technologies, the capacity to generate architectural visualization images founded on provided textual input has now materialized. Termed as the process of text-to-image generation, this procedure holds the capability to engender highly realistic images, thereby serving as a multifunctional instrument for the creation of an extensive gamut of architectural visualization content. In light of the continued evolution of AI technology, text-to-image generation is anticipated to assume a pivotal role within the architectural domain. Consequently, image generative AI augments the prospects of creative potential beyond conventional methodologies.

2.2 Potentials of Generative AI on Architectural Visualization

Architectural visualization plays a crucial role in effective communication during the design process due to the intricate nature of design and spatial characteristics [Chiu, 1995]. Notably, architectural visualization techniques such as 3D modeling provide a comprehensive understanding of spatial relationships [Eastman, 1999]. They serve as essential tools for visually expressing complex designs and enabling clear communication with clients and stakeholders. This facilitates the facile comprehension and assessment of project concepts and designs, enabling the early identification of design flaws, leading to cost and time savings and enhancing satisfaction. In the initial stages of design, they prove particularly effective for comparative analysis and review of various design alternatives. Historically, the generation of architectural visualization images required specialized hardware such as GPUs, along with the utilization of dedicated architectural software. This demanded a significant investment of time and effort, ranging from conceptual design configurations to comprehensive design processes. However, with the advent of generative AI, the landscape has transformed. Now, it is possible to efficiently create numerous architectural visualization images with high-performance GPUs, without the necessity for separate platform installations. Through web browsers, one can seamlessly generate highly detailed, high-quality visual images using text-based commands (prompts). This transformation marks a paradigm shift in architectural visualization, affording designers an unprecedented level of efficiency and versatility in the creation and communication of their spatial visions.

3. INTENSIVE TEST USING GENERATIVE AI FOR SPATIAL LIGHT ANALYSIS VISUALIZATON IMAGE

3.1 Image Generation Test for Spatial Light Analysis Visualization Image

In this study, an examination was conducted to assess the feasibility of employing generative AI, utilizing the open-source image generation model "Stable Diffusion" (2022, Stability AI), for the immediate generation of spatial light analysis visualization images. During the testing phase, emphasis was placed on conducting comparative analyses of text-image generation and visualization performance. Furthermore, the scope was delimited to prioritizing visual effects and approximate simulation result visualization, rather than accuracy and precision. While there are two main approaches for AI-assisted image generation, namely, 1) image-to-image (img2img) and 2) text-to-image (txt2img), the latter method of using AI to generate architectural schematics was adopted for testing purposes.

Prompts were formulated under four categories: 1) Scene Description, 2) Geographic Location, 3) Image Quality, and 4) Light Analysis Conditions. The generated images were set to a resolution of 1024x512 pixels. The testing was conducted using the SD model within a local PC environment. A total of 2,000 images were generated through 200 images per testing scenario. On average, it took approximately 5 seconds to generate a single image.

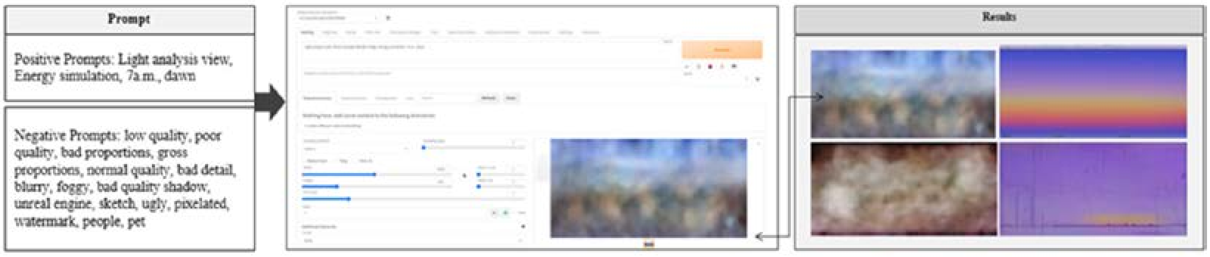


Fig. 1: Procedure for Spatial Light Analysis Visualization Image Generation Test

3.2 Results of Spatial Light Analysis Visualization Image Generation Tests

Based on the results of the previously conducted spatial light analysis simulation visualization tests, the current model has been found unable to generate interior light analysis visualization images of spaces. The lighting simulation visualization images generated through existing image generation models did not exhibit the characteristics of typical simulation images produced using simulation tools, revealing two key issues. Firstly, the model failed to recognize objects composing the space such as windows, ceilings, and walls, as well as lighting fixtures; hence, properties like shading and luminance were not accurately reflected. In essence, these simulation visualizations did not consider the lighting analysis environment. Secondly, there was a lack of consistency in the simulation image outputs, indicative of the absence of defined methods for visualizing quantitative lighting analysis outcomes (view type, visualization style). Consequently, the comparison of design alternatives under uniform conditions became unfeasible. To address these challenges, it is imperative to undergo additional training using lighting analysis images that incorporate the visualization elements and attributes pertinent to lighting simulation. While the existing model proves efficient in generating images across a wide range of domains, enhancing the model's capabilities through additional training is essential for tailored image generation in specific fields due to the constraints posed therein.

4. ADDITIONAL TRAINING FOR VISUALIZING LIGHT ANALYSIS

For the purpose of AI-driven light analysis image generation, an approach involving the following processes: 1) D Definition of the scope of Light Analysis, 2) Data preparation, and 3) Training, is proposed.

4.1 Definition of the scope of Light Analysis

This study focuses on indoor lighting visualization images achievable during the initial stages of interior architecture design through AI methodologies. The light analysis is applicable across the first three stages of design elaboration as outlined in ISO16817 (Project definition – Conceptual design schematic design – Detailed design – Final design). Given that decisions made during the initial design phase significantly influence the subsequent design process direction, preemptively understanding the potential impact of initial design decisions holds paramount importance [Kalay, Y. E. (2004)].

4.2 Data preparation

During the stage of Data Preparation, meticulous consideration was given to the types of training data, the extent of generative scope, and the methods of data creation. Through the utilization of Building Information Modeling (BIM) and rendering techniques for lighting simulation imagery, a process was employed to define the range of light influence elements within the visualization components of lighting simulation, thus facilitating the generation of training data comprising Light Analysis simulation images for indoor spaces.

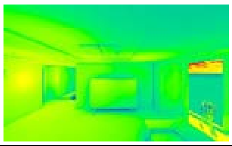
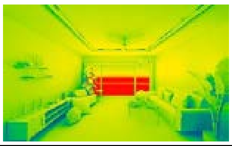
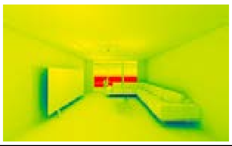
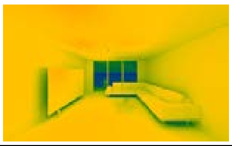
4.2.1 Categorization of Training Data and Scope of Generation

Within the framework of this study, the scope for generating training data was determined based on considerations encompassing spatial design elements, lighting design components, and visualization techniques. Spatial dimensions were confined to the living room, accounting for spatial design elements such as ceilings, floors, walls, and windows (with respective sizes). Lighting design elements were delimited to natural light (primary light source) and specific timeframes (7 a.m., 12 p.m., 6 p.m.), with sunrise at 7 a.m., noon at 12 p.m., and sunset at 6 p.m. The visualization techniques were confined to interior views and photorealistic representations, serving as the basis for generating the training dataset.

4.2.2 Methodology for Generating Training Data and Illustrative Cases

For the process of generating training data, the BIM software named "Revit" was employed to execute interior space (living room) BIM modeling. Subsequent to this, the Revit plug-in program known as "Enscape" was utilized to generate light analysis simulations and rendering images of the modeled interior space. The ensuing outcome images arising from these procedures have been presented in the table indicated by the respective table number.

Table 1: BIM Rendering Image for Additional Training

Training Data Type	Training Data Image			
Light analysis view render image_7a.m.				
Light analysis view render image_12p.m.				
Light analysis view render image_6p.m				

4.3 Training

The Additional training was carried out on a local PC equipped with an RTX A6000 GPU model boasting 47.5GB of memory capacity. Two distinct methodologies were employed for additional training: 1) Fine-tuning of the Stable Diffusion (SD) model using the Dreambooth approach, and 2) Training of the SD model using the Low-Rank Adaptation of large Language Models (LoRA) technique. LoRA, a technology employed for image generative AI fine-tuning, facilitates the creation of additional training model files in a brief time frame without necessitating intensive GPU performance. LoRA enables few-shot learning and offers the advantage of promptly and easily observing the impact of styles by altering model file weights. The resultant ". safetensors" LoRA model files, generated upon completion of additional training, can be copied and utilized on other devices.

Fine-tuned models were developed, categorized into cases of fine-tuning the SD model itself and fine-tuning the SD model with the application of LoRA. Each category encompassed three learning types corresponding to different time frames influenced by natural light (7 a.m., 12 p.m., 6 p.m.). Rigorous hyperparameter configuration and combinations were systematically implemented to facilitate precise additional training. Hyperparameter optimization enhanced the quality of generated training model images. The array of hyperparameters considered in this study ranged from image size, batch size, epoch, Caption Extension, learning rate, learning rate scheduler, to learning rate warmup. Given the utilization of LLM-based models for additional training, the process encompassed engineering and pairing image and text (prompt) data. Prompts were classified into Positive prompts and Negative prompts, based on their application status.

Table 2: Configuration Values of Hyperparameters for Additional Training

Model		Training data				Fine tuning hyperparameters
Base Model	Fine-tuned Model	Image type	Number	Prompt text		
				Positive prompt	Negative prompt	

V1-5-puned ckpt	Model 1	Light analysis view render image_7a.m.	10	Light analysis view, Interior image, Revit, Enscape, Render image, Energy simulation, 7a.m., dawn	low quality, poor quality, bad proportions, gross proportions, normal quality, bad detail, blurry, foggy, bad quality shadow, unreal engine, sketch, ugly, pixelated, watermark, people, pet	· Train Batch Size: 2 · Epoch: 150 · Caption Extension: .txt · Learning rate:0.001 · Learning Rate Scheduler: Constant · Learning Rate Warmup:10
	Model 2	Light analysis view render image_12p.m.	10	Light analysis view, Interior image, Revit, Enscape, Render image, Energy simulation, 12p.m., noon		
	Model 3	Light analysis view render image_6p.m	10	Light analysis view, Interior image, Revit, Enscape, Render image, Energy simulation, 6p.m., dusk		

5. OUTPUTS OF ADDITIONAL TRAINED MODEL

Within the realm of AI-driven image generation, two primary approaches exist: 1) Text-to-Image (txt2img), and 2) Image-to-Image (img2img). The txt2img approach generates architectural visualization images based on given textual descriptions. This process demands precision in design due to its sensitivity to factors such as the words utilized, accurate descriptions, and word arrangement. Nonetheless, this approach offers the advantage of efficiently generating realistic images. In contrast, the img2img approach provides the functionality to manipulate and enhance images or photographs, facilitating their reprocessing and utilization. In this section, we aim to demonstrate the outcomes of the trained additional models using both of these image generation approaches, showcasing their capabilities based on the previously conducted additional training.

5.1 Generation of Visualized Images Using the Text-to-Image (txt2img) Approach

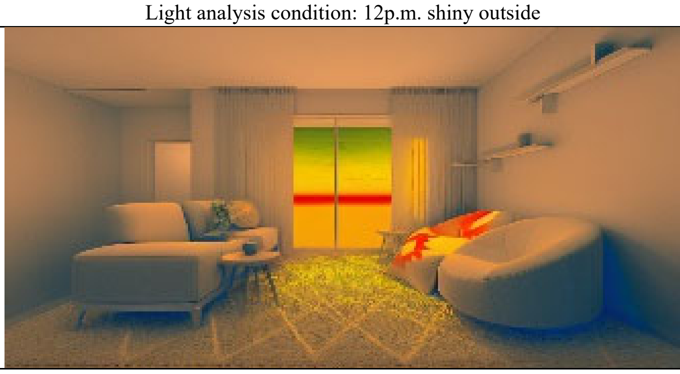
To facilitate a comparative analysis between pre and post additional training outcomes, the identical prompts utilized during the preceding intensive test were employed. Prompts were categorized into Positive prompts and Negative prompts based on their application status. Positive prompts were further classified into Scene Description, Geographic Location, Image Quality, and Light Analysis Condition, generating visualization images of spatial light analysis tailored to the characteristics defined by these prompts.

Table 3: Image Generation from Txt2img Approach

Model	Light analysis view render image_7a.m.	Light analysis view render image_12p.m.	Light analysis view render image_6p.m.
Negative prompt	low quality, poor quality, bad proportions, gross proportions, normal quality, bad detail, blurry, foggy, bad quality shadow, unreal engine, sketch, ugly, pixelated, watermark, people, pet		
Positive prompt	Scene Description : Light analysis view, Interior image, Revit, Enscape, Render image, Energy simulation, Livingroom, large window		
	Geographic location (gps location data,country) : 50, Yonsei-ro, Seodaemun-gu, Seoul, Republic of Korea		
	Image quality: low quality, poor quality, bad proportions, gross proportions, normal quality, bad detail, blurry, foggy, bad quality shadow, unreal engine, sketch, ugly, pixelated, watermark, people, pet		
	Light analysis condition: 7a.m. shiny outside	Light analysis condition: 12p.m. shiny outside	Light analysis condition: 6p.m. shiny outside
Output			

5.2 Generation of Visualized Images Using the Image-to-Image (img2img) Approach

Table 4: Image Generation from Img2img Approach

Input	
Prompt	Scene Description : Light analysis view, Interior image, Revit, Enscape, Render image, Energy simulation, Livingroom, large window
	Geographic location: (gps location data,country) 50, Yonsei-ro, Seodaemun-gu, Seoul, Republic of Korea
	Image quality: low quality, poor quality, bad proportions, gross proportions, normal quality, bad detail, blurry, foggy, bad quality shadow, unreal engine, sketch, ugly, pixelated, watermark, people, pet
	Light analysis condition: 12p.m. shiny outside
Output	

6. CONCLUSION

According to the approach proposed in this study, the utilization of Image Generation AI has yielded the capability to generate visualized light analysis images within spatial contexts during the initial design stage, obviating the need for simulation processes. Notably, even at the nascent phase characterized by mere design concepts, the potential for inferring light influx within a space based solely on text descriptions related to these design concepts was evident. This approach has been substantiated by showcasing its capacity to transform not only text but also 3D rendering images into light analysis visualization images. It is worth noting that this study, with its emphasis on visualization from an architectural perspective over a purely engineering one in the light analysis simulation process, may have certain limitations. Nonetheless, this approach harbors the potential to construct models that yield more precise and accurate light analysis outcomes. Particularly focused on the Stable Diffusion model and conducted as an exploratory endeavor into the architectural visualization potential through Image Generation AI at its nascent stages, there lies an opportunity to derive more intricate results through the utilization of diverse generative AI programs and supplementary functionalities. By incorporating these components, the potential for producing even more detailed outcomes is substantial. Furthermore, through the integration of specific requirements of light analysis simulations and domain knowledge-based additional training, there lies the potential for enhancement, affirming the robust potential of Image Generation AI. This study underscores the substantial potential of Image Generation AI by emphasizing its ability to explore the possibilities of architectural visualization.

7. AKNOWLEDGEMENT

This work is supported in 2023 by the Korea Agency for Infrastructure Technology Advancement (KAIA) grant funded by the Ministry of Land, Infrastructure and Transport (Grant RS-2021-KA163269).

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REAL-TIME GEOMETRY ASSESSMENT USING LASER LINE SCANNER DURING LASER POWDER DIRECTED ENERGY DEPOSITION ADDITIVE MANUFACTURING OF SS316L COMPONENT WITH SHARP FEATURE

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ABSTRACT: *Directed energy deposition (DED) is a major metal additive manufacturing (AM) technology that is increasingly used in many industries due to its ability to manufacture complex components of arbitrary shapes and sizes. However, a lack of timely geometry assessment and the consequent geometry control hinders the development of DED towards zero defect manufacturing. In this study, a real-time geometry assessment methodology is developed for laser pow-der directed energy deposition (LP-DED). A geometry assessment system is developed using a laser line scanner capable of inspecting the melt pool area, the just solidified area, as well as layer-wise inspection. An image processing method with an encoder-decoder based profile completion network was developed to obtain accurate track profile in images from real-time inspection. Experiments have been conducted to validate the proposed methodology by depositing multi-layer X-shape objects.*

KEYWORDS: *Additive Manufacturing, Directed energy deposition, Real-time geometry assessment, Laser line scanning*

1. INTRODUCTION

Metal additive manufacturing (AM) technologies' potential to revolutionize the manufacturing industry has not only been well-recognized but has inspired many fields [1]. According to the American Society for Testing and Materials (ASTM) standard [2], the two main groups of met-al additive manufacturing technologies are directed energy deposition (DED) and powder bed fusion (PBF), both of which have been widely applied in, for example, the aerospace, automobile, and biomedical industries. In recent years, DED has gained attention as a viable manufacturing method in the construction industry where metallic materials are used extensively in distinctive and complex designs [3]. Often, traditional techniques such as hot rolling, cold forming, and extrusion can only produce regularly shaped, prismatic metallic components [4], which limits the potential use of metallic materials in construction and design. DED can complement traditional methods and produce components with almost any shapes with high precision.

However, DED is somewhat plagued by geometry problems [5]. For example, the thicknesses of the deposited ("printed") layers often deviate from their design values [6]. When more and more layers are deposited, heat accumulation tends to cause the layers to spread, increasing their width but decreasing their height [7]. In addition, as the nozzle comes to deposit the object's corners or intersections, the resulting geometry also quite often deviates from the design [8]. The geometrical dimensions of the deposited object often fail to meet the quality requirement or even collapse when geometry deviation occurs during the deposition and is not solved in a timely manner, which will lead to time and cost waste. Moreover, an accurate geometry profile is quite helpful for other quality analysis during the printing process, such as the online stress measurement [9]. Therefore, it is important that the geometry of the printed object is continuously inspected in real time, as more material gets deposited.

Vision cameras and laser line scanners are often employed to assess the geometry of an object being printed via DED [10]. However, though vision cameras can assess the geometry in real-time, only either the track width or track height is measured, but not the whole track pro-file [11]. On the other hand, laser line scanners are mostly used post-DED, at which point the influence of powder and deposition laser is quite small so that the measuring accuracy is high. Besides, previous studies on geometry assessment have tended to focus on single- or multi-layer straight line deposition; multi-layer deposition of components with sharp features such as intersections or corners,

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)

Liu Yang, Boyu Wang, Jack C.P. Cheng, Peipei Liu, Hoon Sohn, *Real-Time Geometry Assessment Using Laser Line Scanner During Laser Powder Directed Energy Deposition Additive Manufacturing of SS316L Component with Sharp Feature,* pp. 965-976, DOI 10.36253/979-12-215-0289-3.97

is important but not well studied. Therefore, the objective of this study is to develop a system capable of conducting real-time 3D geometry assessment during multi-layer deposition of objects with sharp features. There are four main contributions: (1) A geometry assessment system was developed to achieve both real-time inspection and layer-wise inspection during the LP-DED process; (2) In real-time inspection, an image processing method including a novel encoder-decoder based profile completion network was developed to obtain an accurate track profile; and (3) geometry assessment of multi-layer X-shape deposition has been achieved.

This paper is organized as follows. Section 2 gives some background on our research, which includes the working principle of a laser line scanner, a description of LP-DED and geometry assessment during DED. Section 3 explains the developed geometry assessment methodology. Section 4 provides the experimental results and discussion of the proposed methodology. Section 5 concludes the paper by presenting a summary, limitations, and future work.

2. RESEARCH BACKGROUND

2.1 Description of laser line scanner

A laser line scanner is a piece of non-destructive testing (NDT) equipment that has been used successfully to capture the shape of an object. The scanner operates based on the principle of laser triangulation as shown in Figure 2-2. By selecting the bottom of the sensor as a reference as shown on Figure 2-2, the basic triangulation calculation is expressed in equation (1).

$$b_1 = \frac{a_1}{\tan \alpha_1} \tag{1}$$

For laser line scanner, instead of projecting a single point, a laser line is projected on the target surface. After that, the diffusely reflected light of the laser line is detected by a high-quality sensors array called CMOS sensor matrix. Each projected point corresponds to one column on the sensor matrix. Based on the position of the detected laser beam on the corresponding column on sensor matrix, the distance of one measuring point to a defined reference in the sensor (Z coordinate) and can be calculated via triangulation, and the exact position of each point on the laser line (X coordinate) is acquired accordingly.

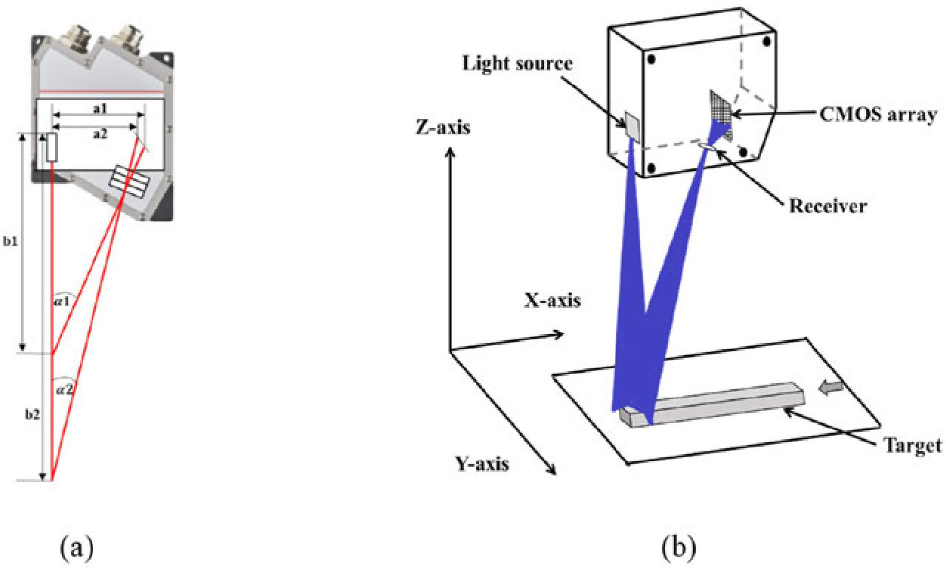


Fig. 1: (a) Principle of optical triangulation, (b) Principle of laser line scanner

In addition, a band filter is embedded right before the CMOS sensor to avoid the reflection of light beyond the expected wavelength, and only captures the reflection of the projected laser line. With respect to laser light, red and blue laser diodes are commonly available for laser line scanners. The red laser scanner is ideal for common measurement tasks especially with extremely dark surfaces whereas the blue laser scanner is ideal for transparent, organic, and red-hot glowing surfaces. In the DED process, when the high power-density laser is focused on a continuous stream of metal powder, the substrate becomes red- hot glowing surface. Thus, for this study a blue laser diode line scanner is used to achieve an accurate result. In addition, the blue laser is preferred to the red one since it is an extremely sharp-focused laser line that does not penetrate the surface.

2.2 Geometry assessment during DED

The geometry assessment targets include the geometry of the melt pool area and the just solidified area as well as the layer geometry of the deposited object. Much research in recent years has focused on inspecting the geometry of the melt pool, since it can be used for real-time geometry control [10]. Camera-based methods are popularly used to inspect the melt pool geometry, including vision camera and infrared camera. Vision cameras can be used to measure either the width or the height of the melt pool depending on the installation location and the target measurement field [11], while infrared cameras are normally used to measure the width and length of the melt pool [17]. Some recent papers have attempted to estimate the melt pool height using infrared cameras with the help of deep learning methods. However, these methods cannot measure the spatial profile of the melt pool area. The inspection of just solidified area is important as it is reported that this can be used for online stress estimation [9]. Moreover, compared with the melt pool area, the just solidified area might better represent the final geometry of the deposited track since thermal shrinking occurs during the solidification process [18]. The just solidified area is quite close to the melt pool area so that some studies use it for real-time geometry control though there is bound to be a small lag. Similarly, camera-based methods are used but a spatial profile cannot be obtained [19]. While laser line scanners can be used to obtain a special profile [20], its performance are affected by powder reflection and high intensity melting laser during LP-DED process, which prevents it from obtaining accurate spatial profile, thus it is often used for layer-wise geometry inspection rather than real-time geometry inspection. The inspection of layer geometry after printing each layer has been studied as well. This method needs to consider inspection path during the design process, which increases design effort and printing time. However, it is applicable to all kinds of printing shapes and toolpaths. In addition, for layer-wise control which does not need instant feedback, it is a better choice [21]. To address geometry assessment of all three targets, a geometry assessment system is developed in this study which aims to achieve both real-time inspection and layer-wise inspection of the track profile using laser line scanner.

Note that the term "real-time" might be ambiguous, as it has been used in a different sense in the literature from field to field. In this study, inspections with the laser line of a line scanner located at just a solidified area or melting pool area are called real-time inspection, where a small delay relative to the deposition is expected. On the other hand, inspection that takes place after each layer has been printed is called layer-wise inspection, since normally a large delay exists.

3. METHODOLOGY

3.1 Overview of the geometry assessment methodology

For real-time inspection, images are captured during deposition. Here there are three apparent problems that would prevent us from obtaining an accurate profile: (1) powder reflection, (2) melt-influenced area and (3) track profile missing, as illustrated in Fig. 4. The following steps are proposed to overcome these three problems.

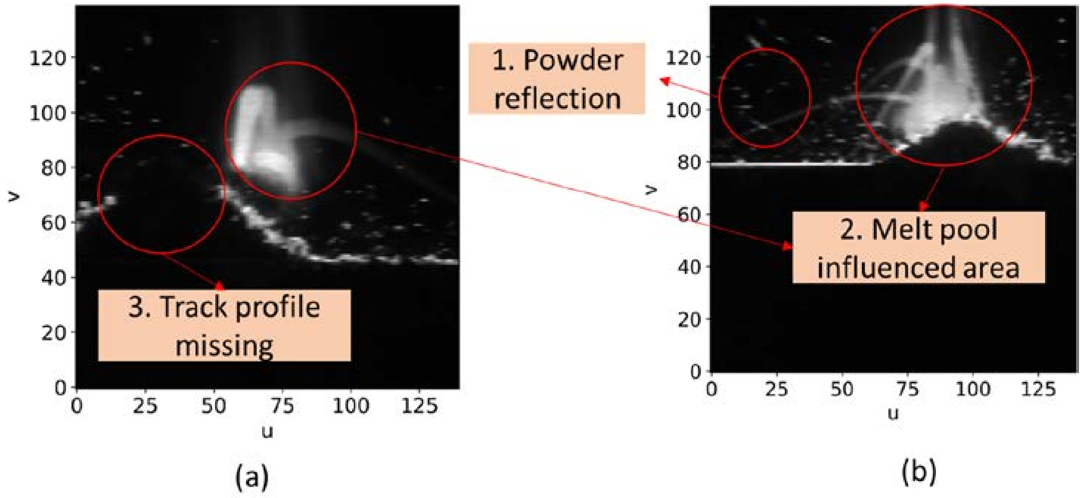


Fig. 4 Problems with raw images: (a) typical profile from real-time inspection of melt pool area, (b) typical profile from real-time inspection of just solidified area

3.2 Powder reflection removal

Firstly, an image enhancement technique, namely contrast stretching, is applied to improve the contrast in each image by converting the original intensity value of a smaller range to a larger range of intensity values, as shown in Eq. (3) and Fig. 5.

$$s = T(r) \tag{3}$$

where r is the input intensity, s is the output intensity, and T is the intensity transformation function. By applying this function, the brighter pixels become even brighter, and darker pixels become even dimmer. Since powder reflection always has lower intensity, it can remove the pixels of powder reflection.

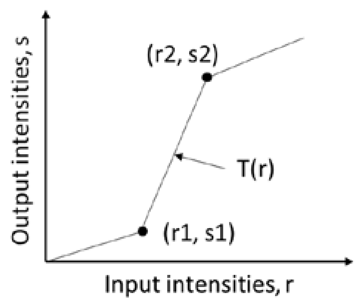


Fig. 5 Powder reflection removal: contrast stretching

3.3 Melt-influenced area removal

To remove the melt-influenced area, a DBSCAN clustering algorithm is applied on the image. As shown in Fig. 6(a), for all non-zero pixels in the image, a core pixel is selected if the pixel has n number of neighbors, where the neighbors are pixels within a distance ε from the core pixel. The distance between two pixels is calculated using Eq. (4):

$$d_{ij} = \sqrt{(u_j - u_i)^2 + (v_j - v_i)^2} \tag{4}$$

where (u_i, v_i) and (u_j, v_j) are the U-V coordinates of pixels i and j. A cluster is formed by recursively taking a core pixel, finding among all of its neighbor pixels that are core pixels, in turn finding all of their neighbors that are core pixels, and so on. After clustering, the cluster with the largest mean v value will be removed. For some images, the melt-influenced area will be connected to the track profile, and the track profile will be removed as shown in Fig. 6 (b). To solve this problem, a modified DBSCAN is proposed by adding an additional coordinate m to represent the distance to the lowest non-zero pixels for each column as illustrated in Fig. 6 (c) and the distance between two pixels is calculated using Eq. (5). After that, the DBSCAN algorithm is applied, and the result can be seen in Fig. 6(d)

$$d_{ij} = \sqrt{(u_j - u_i)^2 + (v_j - v_i)^2 + (m_j - m_i)^2} \tag{5}$$

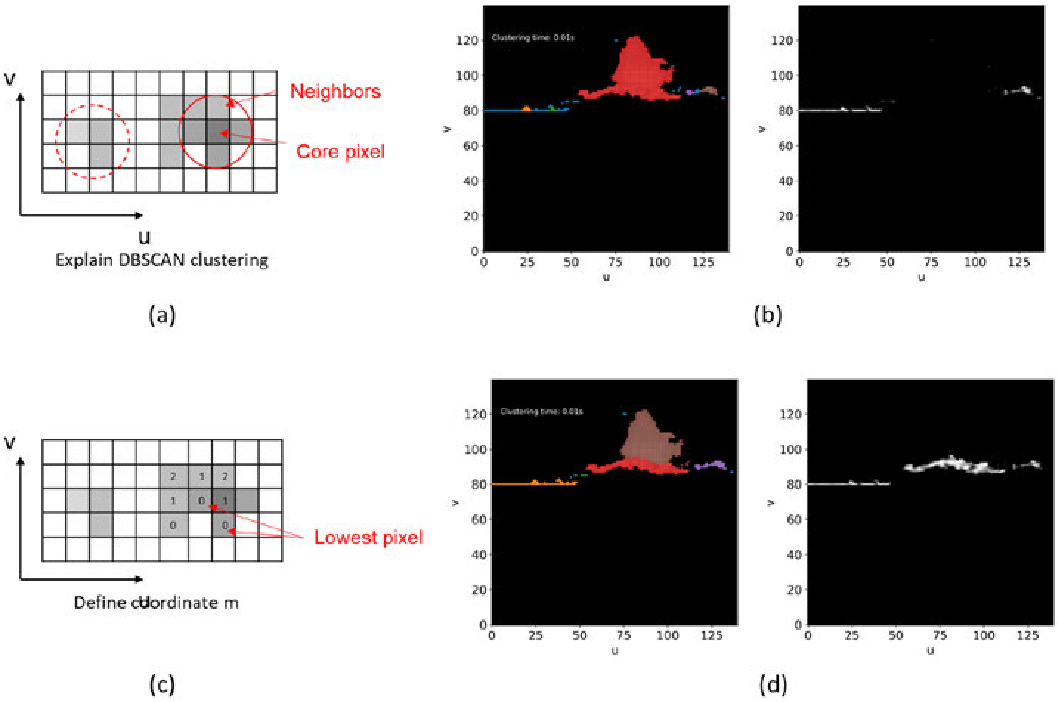


Fig. 6 Melt-influenced area removal: (a) explain DBSCAN clustering on the image, (b) directly apply DSCAN, (c) add coordinate m and (d) apply modified DBSCAN

3.4 Encoder-decoder based profile completion

After melt-influenced area removal, the track profile is extracted. However, there exists severe profile missing problems, which will severely deteriorate the quality of 3D point cloud for geometry assessment. The profile missing problem is mainly due to bad reflection on the deposited metal surfaces, especially when there is high-intensity laser radiation from the printer. As shown in Fig. 7, the cross-sections at different locations on the X-shape represents different types of profile missing, and a pattern can be observed for each track: (1) at the beginning of each track (location A), the opposite side of the melt-pool influenced area are missing for the one-peak cross section; (2) when approaching the intersection (location B), the line scanner captures two-peak cross section and the middle part of the two-peak cross section is missing; (3) at the intersection (location C), the top part of the one-peak cross section is missing; (4) when getting away from the intersection (location D), two side parts of the two-peak cross section are missing; (5) at the end of each track (location E), same as in location A, the opposite side missing of one-peak cross-section can be observed. For such varied types of profile missing problems, traditional completion methods such as curve fitting [22] or interpolation methods cannot achieve satisfied result, especially for the middle part missing of two-peak cross section.

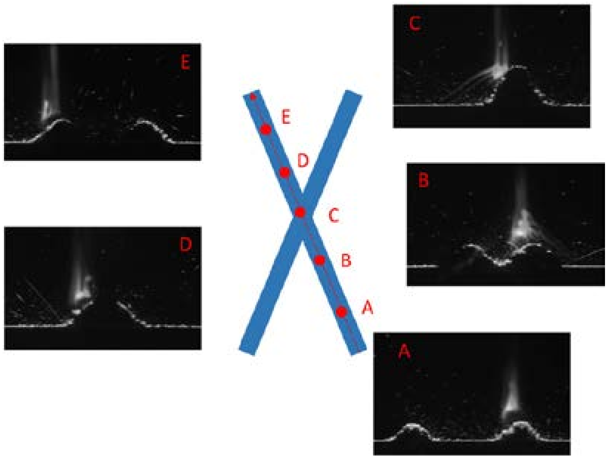


Fig. 7 Track profile missing problem

To complete the track profile in captured images, an encoder-decoder based profile completion algorithm is proposed. The idea of adopting an encoder-decoder based network comes from point cloud completion techniques. Encoder-decoder based networks are widely used in 3D point cloud completion tasks [23], [24], as the encoder can summarize the geometric information from an incomplete input point cloud to form a feature vector, and, based on the feature vector, the decoder will predict the complete shape of the point cloud. The proposed algorithm is revised from DeepLabv3+ [25], which is a popular encoder-decoder network with images as input.

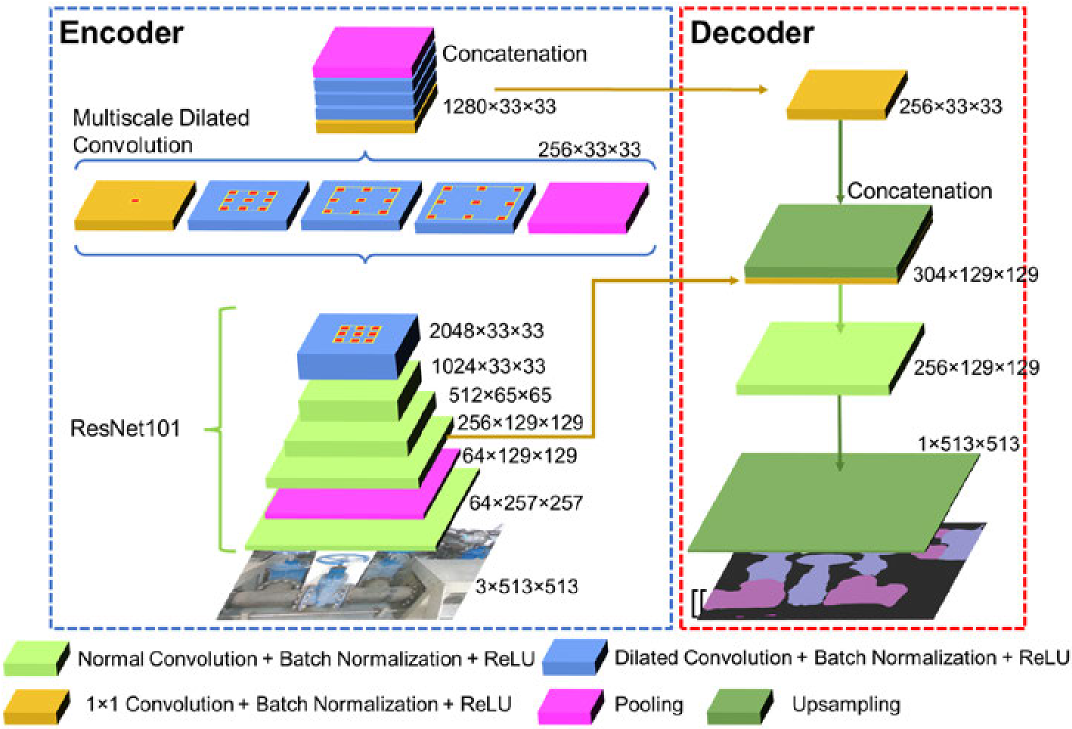


Fig. 8 Proposed encoder-decoder based profile completion network

In this study, the useful information in preprocessed images is the track profile pixels, which take up a small proportion of the whole image. Therefore, to make an efficient use of information in the images, the images from previous steps are further converted to 1D array and fed as input. A novel deeplab1D network is proposed which changes 2D operation in all layers of the DeepLabv3+ network to a 1D operation. Moreover, since previous profiles might provide useful information for the completion of current profile, therefore the previous (t – 1) profiles are considered as input for the proposed network. When t equals 1, only the current profile is considered.

The architecture of the proposed encoder-decoder based network is shown in Fig. 8. First, the image of 140 × 220 pixels from previous steps is converted into a 1 × 220 array. For each column of the array of the image, the gravity of the intensity plot on the v axis is taken as one of the values in the 1 × 220 array. The 1 × 220 array is inputted into the proposed network, which includes an encoder and a decoder. The encoder consists of a ResNet1D and an ASPP1D module. The ResNet1D module is based on ResNet-101 [26]. The ASPP1D module has evolved from Atrous Spatial Pyramid Pooling (ASPP) [27], which conducts several parallel Atrous convolutions with different rates. An Atrous convolution is described in Eq. (6).

$$y[i] = \sum_{k} x[i + r \cdot k]\, w[k] \tag{6}$$

where i is the location on the output feature map y, w is a convolution filter applied over the input feature map x. The Atrous rate r determines the stride that samples the input signal. Note that an Atrous convolution with $r = 1$ is equal to a standard convolution. In the encoder module, the concatenated output from ASPP1D is processed by a 1 × 1 convolution and an interpolation by a factor of 4, then concatenated with the convolved low-level feature from the ResNet1D. After this concatenation, a few convolutions are applied to refine the features followed by interpolation by a factor of 4 to recover the final output shape (a 1 × 220 array).

3.5 Point cloud generation

The captured data from real-time inspection and layer-wise inspection is in its local coordinate system. For subsequent geometry assessment, such as comparing as-designed geometry with as-built geometry, the captured data needs to be converted to the global coordinate system. For real-time inspection, the U-V to X-Z coordinates conversion and X-Z coordinate transformation are needed to obtain the point cloud of target cross-section from captured images. While for layer-wise inspection, 2D points are collected, thus only X-Z coordinate transformation is conducted.

Since the commercial line scanner normally uses a CCD sensor to capture its emitted laser reflection on the target surface, this process can be modeled using a pin-hole model, which is the basis camera model based on the perspective projection principle [28].

First, intrinsic calibration is conducted, which is to reconstruct the X-Z coordinates in the real-world coordinate system, given the U-V coordinates in the image coordinate system using the following equation.

$$\begin{bmatrix} x_l \\ z_l \\ 1 \end{bmatrix} = \begin{bmatrix} k_{11}' & k_{12}' & k_{13}' \\ k_{21}' & k_{22}' & k_{23}' \\ k_{31}' & k_{32}' & k_{33}' \end{bmatrix} \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} \tag{10}$$

By getting several pairs of U-V and X-Z coordinates, a least-square solution can be used, and the intrinsic transformation matrix K can be obtained.

Second, after obtaining the X-Z coordinates in the line scanner's local coordinate system (X_L, Z_L), a translation matrix is needed to convert the X-Z coordinates into the global coordinate system (X_G, Z_G), which is the extrinsic calibration process. After installing the laser line scanner, a rectangular calibration bar with known dimension is put at the origin of the global coordinate system, thus the as-designed cross section profile of the calibration bar in the global coordinate system can be obtained. Finally, after obtaining coordinates of measure profile in nozzle's coordinate system, the 3D coordinates of the measured profile in the global coordinate system can be calculated by fusing the nozzle's position using Eq. (16).

$$\begin{bmatrix} x_g \\ y_g \\ z_g \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & tx_2 \\ 0 & 1 & 0 & ty_2 \\ 0 & 0 & 1 & tz_2 \end{bmatrix} \begin{bmatrix} x_n \\ y_n \\ z_n \\ 1 \end{bmatrix} \tag{16}$$

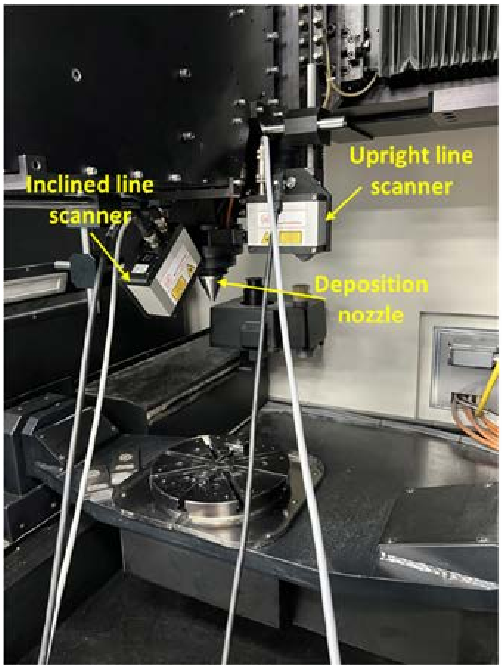
where the tx_2, ty_2 and tz_2 are the coordinates of the printing position in the global coordinate system, i.e., the nozzle's position. To obtain the nozzle's position for each captured profile, a log file is extracted from the DED printer during deposition which contains the location of the nozzle and a timestamp at each location.

4. EXPERIMENT AND DISCUSSION

4.1 Experiment setup

The LP-DED printer used in this study is an InssTek MX-400, which is a commercial metal printer equipped with a 5-degree-of-freedom mechanical moving stage, a Ytterbium fiber laser with a wavelength of 1070 nm, a maximum power of 1kW, and a focal laser beam diameter of 800 µm, as well as a metal powder delivery system with shield gas and carrier gas (Argon gas). A 316 L stainless-steel powder with an average particle size of 100 µm was used for deposition and a substrate using the same material as the powder with dimensions 100 mm × 50 mm × 10 mm was placed on the moving stage.

Two laser line scanners (Micro-Epsilon scanCONTROL 3000-25/BL), an inclined line scanner and an upright line scanner (Fig. 13), are installed for real-time and layer-wise inspection, respectively. Calibrations are conducted for both line scanners to get the transformation matrix used for 3D point cloud generation before deposition. For the inclined line scanner, intrinsic and extrinsic calibration are conducted; for the upright line scanner, only extrinsic calibration is needed. The exposure time was set to 20 ms (determined based on experience) to get a better reflection from the metal surfaces. The deposited object is a 20-layer X-shaped object. Two experiments are conducted: Experiment 1: deposition with real-time inspection of melt pool area ($d = 0mm$) and layer-wise inspection; Experiment 2: deposition with real-time inspection of just solidified area ($d = 3mm$) and layer-wise inspection.



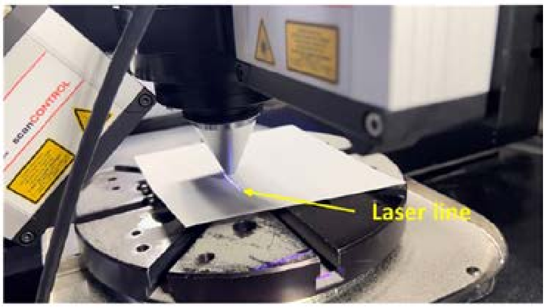


Fig. 13 Experiment setup: Geometry assessment system

4.2 Processing result

During the deposition of each layer, the inclined line scanner with laser line pointing at the melt pool or just solidified area captures and transfers images to the software for processing. After the deposition of each layer, layer-wise inspection is conducted by the upright line scanner, and point profiles are collected. For layer-wise inspection, 2D points of each cross-section are obtained and 3D point cloud data can be generated using extrinsic calibration matrix and fusing printer information. For real-time inspection, powder reflection removal and melt-influenced area removal are conducted for each image. Then the developed encoder-decoder based profile completion network is used to complete the profile on each image and the U-V coordinates are obtained. Finally, a 3D point cloud data of the deposition X-shape object in the global coordinate system can be generated using the proposed method.

Two experiments are conducted and each with 20 layers of data collected. Experiment 1 collects 1167 images and Experiment 2 collects 1157 images in total. Given the traverse speed of the printer (10 mm/s) and the total tool path length of each deposition (993.86 mm), the actual profile rate of the real-time inspection is about 12 frames per second. In this study, the paired image data from experiment 1 is used for model training and validation, which is divided into training and validation data in a ratio of 0.8, 0.2, respectively. The collected data from experiment 2 is used for model testing. The training process was conducted on GPU (NVIDIA GeForce GTX1080) using Python 3.9, Pytorch 11.7 and CUDA 11.8. Since previous profile is considered, t equals 1 to 5 are considered. For each t value, 80 epochs are trained, the validation dataset is used to choose the best model, then the best model is used for testing.

Root mean squared error (RMSE) was calculated between the output prediction array and the ground truth array. The average RMSE of all profiles in each layer was obtained for each t for comparison (Table 4). For higher layers, the RMSE becomes larger. This is due to the fact that when the layer height becomes higher, the sides of the deposited object will have a more inclined angle of 90 degrees, resulting in a worse reflection of the laser from the line scanner projected on the side of the deposited object. Thus, there will be a more serious profile missing problem for the higher layers, making it more difficult to complete the profile. In addition, when the absolute deposition height increases, the network prediction error also tends to increase, but the proportion of the error with respect to absolute deposition height may remain the same. Therefore, an RMSE-H ratio is calculated for each layer, which is the RMSE error divided by the design height (Table 4). As seen, there is not much difference in the RMSE-H ratio for each layer. The RMSE-H ratio of the first few layers is larger. Considering that the profiles of the first five layers are not seriously missing and the completion model may not be effective in such cases, the profile completion can be applied to the higher layers without the first five layers. When more previous layers are involved, there is little difference in the performance of the proposed model. A slight decrease of RMSE can be observed when t equals 2. Therefore, the model with $t = 2$ is finally selected as the profile completion model in our geometry assessment system, which can generate point cloud with an RMSE of 0.21 mm compared with the ground truth.

Table 4: Test results of the proposed model for different values of t

Test result		As-designed height (mm)	RMSE (mm)					RMSE-H ratio				
			$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$
Layer	1	0.2	0.03	0.03	0.03	0.04	0.03	16%	14%	16%	18%	15%
	2	0.4	0.06	0.05	0.06	0.06	0.06	14%	13%	14%	14%	14%
	3	0.6	0.07	0.07	0.08	0.08	0.08	12%	11%	13%	13%	14%
	4	0.8	0.10	0.09	0.10	0.10	0.11	12%	11%	13%	12%	14%
	5	1	0.11	0.10	0.11	0.12	0.13	11%	10%	11%	12%	13%
	6	1.2	0.13	0.12	0.14	0.14	0.16	11%	10%	12%	11%	13%

	7	1.4	0.16	0.15	0.18	0.18	0.19	12%	11%	13%	13%	13%
	8	1.6	0.16	0.17	0.18	0.19	0.20	10%	10%	11%	12%	13%
	9	1.8	0.20	0.18	0.20	0.19	0.21	11%	10%	11%	11%	12%
	10	2	0.19	0.18	0.20	0.19	0.21	9%	9%	10%	10%	11%
	11	2.2	0.22	0.20	0.22	0.22	0.23	10%	9%	10%	10%	11%
	12	2.4	0.23	0.23	0.23	0.22	0.25	10%	10%	10%	9%	10%
	13	2.6	0.25	0.24	0.25	0.23	0.26	9%	9%	9%	9%	10%
	14	2.8	0.28	0.29	0.28	0.30	0.31	10%	10%	10%	11%	11%
	15	3	0.27	0.27	0.28	0.30	0.33	9%	9%	9%	10%	11%
	16	3.2	0.31	0.29	0.30	0.31	0.33	10%	9%	9%	10%	10%
	17	3.4	0.38	0.36	0.36	0.38	0.37	11%	10%	11%	11%	11%
	18	3.6	0.40	0.38	0.39	0.39	0.39	11%	11%	11%	11%	11%
	19	3.8	0.40	0.38	0.38	0.41	0.41	11%	10%	10%	11%	11%
	20	4	0.43	0.42	0.42	0.44	0.45	11%	11%	10%	11%	11%
	Overall		0.22	0.21	0.22	0.22	0.24					

5. CONCLUSION

This study has developed a real-time geometry assessment methodology for LP-DED using laser line scanner. A geometry assessment system has also been developed to achieve real-time inspection of the melt pool area and the just solidified area, as well as layer-wise inspection of the layers' geometry. An image processing method has been proposed including powder reflection removal, melt-influenced area removal and an encoder-decoder based profile completion network to obtain track profile on images. Then a point cloud generation method was developed including U-V to X-Z coordinates conversion, X-Z coordinate transformation, and 3D point cloud generation by fusing printer information. Experiments have been conducted to validate the proposed method and the result shows that an average RMSE of 0.21 mm can be achieved from point cloud comparison between the point clouds obtained in realtime and obtained layer-wise. The proposed real-time inspection method was able to achieve better performance compared with the line scanner's built-in method, and the developed encoder-decoder profile completion model has been validated which outperforms baseline model. The deposition heights of the melt pool and solidified layer were compared, and the result showed that the differences were not significant using the proposed method.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (grant number: 2019R1A3B3067987).

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OPTIMAL NUMBER OF CUE OBJECTS FOR PHOTO-BASED INDOOR LOCALIZATION

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ABSTRACT: *Building information modeling (BIM) is widely used to generate indoor images for indoor localization. However, changes in camera angles and indoor conditions mean that photos are much more changeable than BIM images. This makes any attempt at localization based on the similarity between real photos and BIM images challenging. To overcome this limitation, we propose a reasoning-based approach for determining the location of a photo by detecting the cue objects in the photo and the relationships between them. The aim of this preliminary study was to determine the optimal number of cue objects required for an indoor image. If there are too few cue objects in an indoor image, it results in an excessive number of location candidates. Conversely, if there are too many cue objects, the accuracy of object detection in an image decreases. Theoretically, a larger number of cue objects would improve the reasoning process; however, too many cue objects could lead to declining object detection performance. The experimental results demonstrated that of two to five cue objects, three cue objects is most likely to yield optimal performance.*

KEYWORDS: *indoor location determination, BIM, reasoning*

1. INTRODUCTION

Photos are commonly used as a medium to support building maintenance and defect management (Kim et al., 2014). These photos are sometimes taken by experienced field workers, but most are captured by unskilled workers or individuals with a limited understanding of the building, such as occupants (Kang et al., 2019). In existing maintenance systems, users are typically required to manually tag the locations where a photo was taken to utilize the system effectively. In particular, when occupants report defects, the specific locations and conditions of the defects are often described in unstructured text, making management even more challenging. Various methods have been used to accurately determine the locations where photos were taken. Several image-based indoor positioning methods have been explored, including approaches which search for the most similar BIM screenshot image to a target photo (Ha et al., 2018) or regress the camera position using deep learning algorithms (Acharya et al., 2019). Nevertheless, image-based methods typically rely on extensive image training and are sensitive to changes in indoor conditions (Kim & Kim, 2023). This sensitivity becomes especially problematic in buildings that have multiple varying factors, including interior fittings and lighting.

To overcome these limitations, especially the sensitivity to changes in indoor conditions, we propose an indoor localization method based on reasoning-based localization method that uses cue objects and their spatial relationships. Unlike furniture, cue objects, such as doors and windows, can serve as stable reference points because they rarely change. To achieve this goal, the first step is to determine the optimal number of cue objects required. If there are too few cue objects, they may not provide sufficient information for localization. However, if there are too many cue objects, the accumulated accuracy of cue-object detection decreases. The aim of this preliminary study was to validate our proposed method by determining the optimal number of cue objects required in an image to accurately locate the positions of indoor photos. To select the optimal number, we developed a prototype localization method based on the spatial relationships among cue objects, which involved comparing the similarities between cue objects and their spatial relationships in a target indoor image with those in a BIM model. We evaluated the performance of the proposed method by varying the number of cue objects in an indoor image, using the mean probability to accurately determine the location where the image was taken. To validate the proposed method, we measured the performance using the mean probability of localization and varied the number of objects within the photos.

This paper consists of five sections. Following this introduction, the second section discusses previous studies related to the research. The third section describes the research methodology and explains the details of the experiments. The fourth section presents the analysis and results of the experiments, and the final section concludes the paper by discussing the main findings, contributions, and limitations of the research.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Youngsun Chung, Daeyoung Gil, Ghang Lee, *Optimal Number of Cue Objects for Photo-Based Indoor Localization,* pp. 977-987, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.98

2. BACKGROUND

2.1 Indoor Localization Using Images

Recent developments in computer vision have led to many attempts at indoor localization. Ha et al. (2018) suggested an indoor localization approach using BIM and a visual geometry group (VGG) model (Simonyan & Zisserman, 2015). They used the proposed model to retrieve the most similar BIM screenshot image to a given photo and to determine where the photo was taken. Alam et al. (2022) conducted a similar investigation based on recurrent neural networks (RNNs) to find the correct position of an indoor camera. These methods were intuitive and moderately effective but sensitive to variations in indoor decorations and lighting conditions arising due to their reliance on identifying the most similar screenshot images.

To enhance robustness, developers have attempted to utilize image datasets with camera trajectory data. In the context of BIM-PoseNet (Acharya et al., 2019) and related studies, various researchers have trained models based on deep convolutional neural networks (DCNNs) and large datasets of indoor BIM screenshot images to determine the positions and angles of the cameras used to capture photos. Two such studies were based on RNNs (Acharya et al., 2020) and channel-wise transformer localization (CT-Loc; Kim & Kim, 2023). Although BIM-PoseNet and CT-Loc applications are robust under varying lighting conditions due to an edge extraction method, they still cannot adapt to changes in furniture arrangements or interior decorations. Additionally, the studies were limited to the fixed linear paths of the cameras and excluded the simultaneous handling of close-range and wide-angle images. However, close-up photos are typically taken to capture the appearance of small-sized defects clearly, but for effective building defect management, both wide- and close-range images are required (i.e., photos need to be taken from a distance to address defects that cover a wide area or where the spatial context of the defects is crucial).

2.2 Indoor Localization Using Objects

To overcome the problem of condition changes in images, several researchers have proposed methods that utilize objects within images for indoor localization. Bay et al. (2006) investigated image-based indoor localization using speed-up robust features (SURF; Guan et al., 2016) and unique landmarks, such as posters or logos. Similarly, Li et al. (2022) used multiple visual landmarks and incorporated smartphone compass readings to improve performance. However, using posters as references is not practical because posters may change frequently, causing difficulties in keeping indoor landmark databases up to date.

To overcome these limitations, our author team proposed a method that used semantic segmentation and pose estimation for the positions of cue objects in indoor photos. They aimed to identify the indoor location where the cue objects in photos and conducted a proof-of-concept study (Kim, 2022). However, the method was only tested on objects photographed at relatively short distances.

In summary, previous localization methods based on images have revealed weaknesses in analyzing images under varying conditions. While the methods that employed edge-rendered images and semantic segmentation proved helpful in increasing the robustness of localization under different lighting conditions, they were still ineffective in capturing changes in interior items or furniture. As a solution, we previously proposed a method that focused on cue objects that rarely changed over time, such as light switches and fire extinguishers, and conducted a preliminary study (Kim, 2022). To further develop the method, in this study, we conducted a set of experiments to determine the optimal number of cue objects required for the method.

3. RESEARCH METHOD

The research flowchart for this study is depicted in Fig. 1. The indoor localization method first obtains information about cue objects and their spatial relationships using computer vision technology. We trained and validated the object detection model on an object detection training dataset using the object types and spatial order of the bounding boxes detected to reason indoor locations by comparing them with the spatial relationships among BIM cue objects. This method is based on left–right relationships of cue objects. Location reasoning may result in one or more specific sets of candidate cue objects. Each candidate represents a potential location depicted in the image. We evaluated the performance of the reasoning model based on the probability of accurately determining the location where the photo was taken, considering the number of candidates and the object detection accuracy. We tested the method with varying numbers of cue objects and found the optimal number when the model achieved the highest performance.

In the experimental phase, to which this paper relates, we began by determining the types of objects that would be used as cue objects and establishing the range of objects present in the image. We then created a sample for the BIM model of a housing unit, shown as a BIM DB in Fig. 1, which incorporated 10 different types of cue objects across 11 rooms. We generated 12,861 BIM screenshot images and used 12,671 images to train and validate the object detection model. We employed the remaining 190 images, each of which included 2–5 cue objects, to evaluate indoor localization performance and find the optimal number of cue objects.

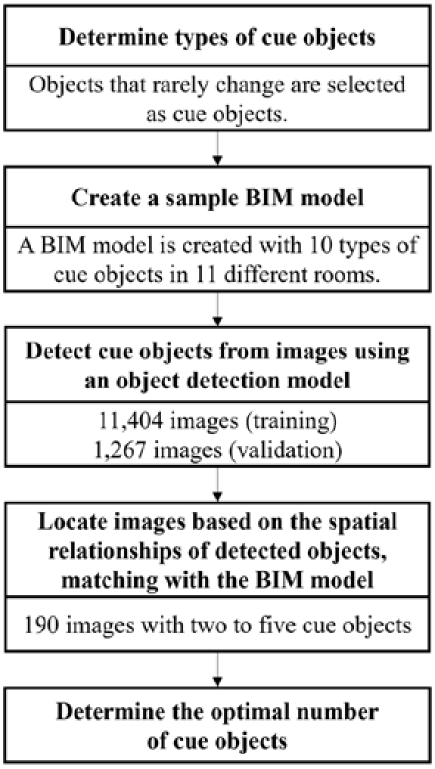

Fig. 1: Research flowchart

3.1 Selection of Cue Objects

For the experiments, we set the following criteria for cue objects:

1) The appearances or positions of cue objects should rarely change; thus, transient items, such as tables and posters, should not be considered cue objects.

2) Ideally, objects should be unique to a certain space and representative of the space. However, since a few objects remain constant over time and are exclusive to a particular space, non-unique objects, such as light switches or doors, could also be considered cue objects.

To determine positions using the spatial relationships among objects that remained relatively constant, we selected objects that fulfilled the above criteria, which resulted in the 10 cue objects listed in Table 1, including three types of doors, a window, a power socket, a light switch, a sink, a toilet bowl, a showerhead, and a kitchen cabinet, being chosen for the experiments.

3.2 BIM Model Creation

We created a sample BIM, we created a model of a housing unit for the experiment. Fig. 2 presents the axonometric view and the plan of the unit model. The model consisted of 11 rooms (the living-dining-kitchen [LDK] space, bedroom 1, bedroom 2, bedroom 3, bedroom 4, bathroom 1, bathroom 2, pantry, closet, balcony, and entrance), all of which had boundary walls, except for the LDK space and the entrance. Although some rooms were significantly different from one another (e.g., bedroom 1 and 2), there were also similarities between certain rooms (e.g., bedrooms 2 and 3). Table 1 provides detailed room information for the housing unit, including the room number, name, and list of cue objects present inside each room, along with their respective quantities. We placed the cue objects in plausible locations and varied their numbers and placements. We classified cue objects with differing appearances within the same category as distinct types. For example, we categorized doors into three different types. Doors A and B were both indoor wooden doors, but door B differed from door A by having two panels. Meanwhile, door C was a steel front door.

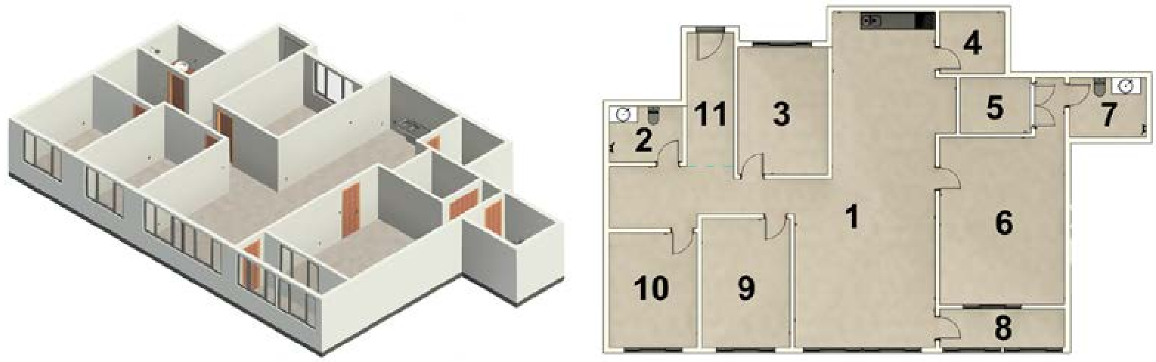

Fig. 2: Axonometric view of the housing unit model (left) and plan of the unit (right)

Table 1: Room information (number, name, and cue objects) for the BIM model of housing unit

Room Number	Room Name	Object Name and Quantity
1	LDK	Door A, 7; Window, 2; Power socket, 8; Light switch, 5; Kitchen cabinet, 1
2	Bathroom 1	Door A, 1; Power socket, 1; Sink, 1; Toilet, 1; Showerhead, 1
3	Bedroom4	Door A, 1; Window, 1; Power socket, 1; Light switch, 1
4	Pantry	Door A, 1; Power socket, 1
5	Closet	Door B, 1; Power socket, 1; Light switch, 1
6	Bedroom 1	Door A, 2; Door B, 1; Window, 1; Power socket, 4; Light switch, 2
7	Bathroom 2	Door A, 1; Power socket, 1; Sink, 1; Toilet, 1; Showerhead, 1
8	Balcony	Door A, 1; Window, 2; Power socket, 1
9	Bedroom 3	Door A, 1; Window, 1; Power socket, 1; Light switch, 1
10	Bedroom 2	Door A, 1; Window, 1; Power socket, 1; Switch, 1
11	Entrance	Door C, 1

3.3 Image Dataset Preparation

To train the model and evaluate the performance of the indoor localization method, we generated 12,861 BIM screenshot images, of which 12,671 were used for object detection and 190 for indoor localization method evaluation. Specifically, we used 11,404 images (roughly 90% of the object detection dataset) for training and 1,267 images for model validation. The dataset with 190 images for the indoor localization method was labeled differently from the previous dataset. The dataset for object detection was labeled according to bounded boxes, whereas the dataset for localization was annotated according to the information for the target room. Table 2 shows the major characteristics of the two image datasets. We created the dataset for object detection using a script that automatically captured the appearance of objects within the BIM model and labeled them accordingly. However, we manually created the dataset to validate the indoor localization method by directly capturing BIM model views.

Table 2: Characteristics of each image dataset

	Dataset for object detection	Dataset for indoor localization method evaluation
Purpose	To train and validate the object detection model	To validate the indoor localization method
Labeling	Cue objects with bounded boxes	Rooms and associated cue objects
Data size	11,404 (training)/1,267 (validation)	190 (validation)
Creation method	Automatically captured BIM model views	Manually captured BIM model views
Image size	785 × 785	1024 × 767

The images used for training and validating the object detection model were square, measured 785 pixels on each side, and were rendered in a realistic style. The dataset creation method is depicted in Fig. 3. We employed visual scripting to automatically generate these images. The viewing point from the camera's location and the target point where it is directed are both required to capture BIM screenshots. We began the viewing point and target point acquisition process by extracting room boundaries from the model and calculating the midpoint of each boundary side. We established viewing points by vertically elevating the midpoint of each boundary 150 cm from the floor to position the camera at average eye level. Viewing points were positioned along room boundaries rather than at the room centroids to capture images from the maximum distance within a room and thereby capture a greater number of cue objects. The scale of the captured objects was similar to that of the objects captured in the indoor localization method evaluation dataset when the viewing points were positioned along room boundaries. We then set target points by vertically elevating the midpoint of each boundary, spanning 40–200 cm, at intervals of 20 cm from the floor. To capture the desired views, we positioned a camera with a field of view (FOV) of 50°, which is the base angle of a normal lens, at the viewing point and directed it toward the target points. We repeated this process for each room in the BIM housing unit model. We produced the initial BIM images using Dynamo. Each was 1,047 × 785 pixels and was subsequently cropped into left, center, and right portions to create 785 × 785-pixel images. We removed redundant images that did not contain any cue objects. In total, we generated 12,671 images and used them to train and validate the object detection model.

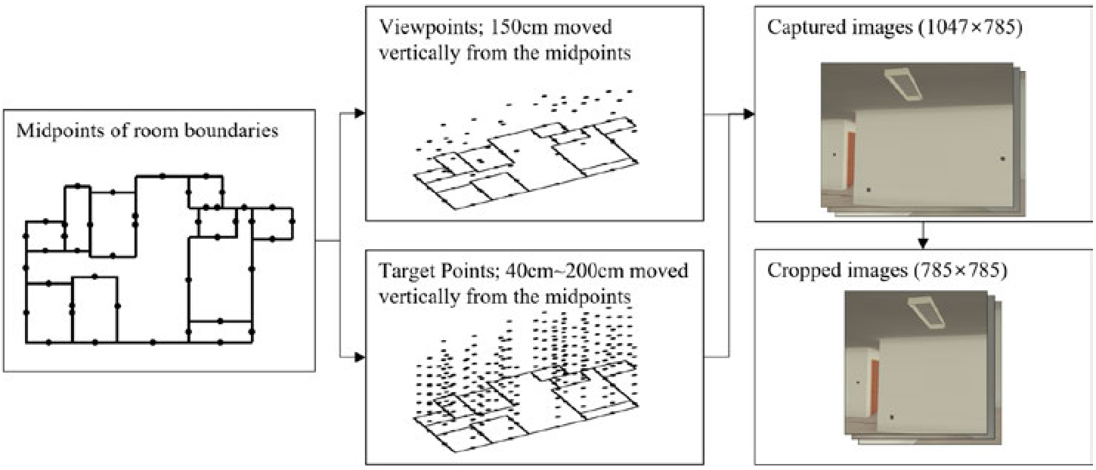

Fig. 3: Dataset creation for the object detection model

Additionally, we manually generated 190 images with varying numbers of cue objects, ranging from two to five, to determine the optimal number of cue objects for an image. The images were divided based on the number of cue objects (n) present in each image. We determined the range of n based on the following rationale: To deduce the location based on the spatial relationship between objects, at least two cue objects were minimally required. For the maximum number of cue objects, assuming that all cue objects were accurately detected, having more cue objects in the image made it easier to accurately determine the location. However, it was very unlikely for an image to include more than five cue objects. Moreover, as the number of cue objects necessary for the proposed method increased, the cumulative object detection error rate increased accordingly. Therefore, we set the maximum n-value to 5. Table 3 provides the distribution of images across the rooms. For scenarios with 2, 3, or 4 cue objects, 50 images were captured for each scenario. For scenarios with 5 cue objects, 40 images were captured, due to the limited existence of views that met the criteria. We determined the number of images for each room based on the availability of the desired view and the size of the room. Initially, we assessed whether each room could provide a view with a certain number of cue objects within the FOV of 50°. Then, considering the available rooms, we allocated the number of images for each room proportionally based on their respective areas. As shown in Table 3, the number of available rooms decreased significantly as the number of cue objects in the image increased. To fulfill the research objective, the image needed to include all contiguous cue objects. Further details regarding this condition will be discussed in Section 3.4.

Table 3: Number of images taken for each room

	Number	1	2	3	4	5	6	7	8	9	10	11	Total
Room information	Area (m^2)	60	5	14	5	5	27	5	6	13	12	8	160
	Cue object quantity	23	5	5	2	3	10	5	5	5	5	1	69
Number of images	$n = 2$	20	2	5	0	2	9	2	2	4	4	0	50
	$n = 3$	20	2	5	0	2	9	2	2	4	4	0	50
	$n = 4$	29	2	0	0	0	13	3	3	0	0	0	50
	$n = 5$	34	0	0	0	0	6	0	0	0	0	0	40

3.4 Object Detection

We used You Only Look Once (YOLO) (Redmon et al., 2016) for this study, which is one of the most widely used networks for object detection. We trained the model using 11,404 images and set aside 1,267 images for model validation. To rationalize the indoor location and the spatial relationships among cue objects within an image, we applied the trained object detection model to the indoor localization method evaluation image dataset, which varied the number of cue objects contained in each image.

3.5 Indoor Location Reasoning

The goal of indoor location reasoning is to determine the locations at which the positional relationships between cue objects obtained through object detection in the images align with the positional relationships the cue objects have within the BIM model. This involves analyzing the X and Y coordinates of the bounding boxes of cue objects in the images to infer whether one object is to the left or right of another object, or above or below it. However, in this experiment, we specifically focused on the left–right relationships between cue objects, as they tended to have fewer variations and provided greater accuracy. Based on the object detection results, we created a cue object list by arranging the objects in ascending order according to their X-coordinate values.

To identify the locations where the BIM information matched the information from the image, we considered how the model's information would manifest in the image. To determine which objects could be observed to the left or right of a specific object when taking a photo, we employed clockwise ordering of the objects present in each room. First, we extracted the positions of the cue objects and the room boundaries, which enabled us to determine the locations and relationships of cue objects within each room. Based on the extracted information, we sequentially listed all the objects in a clockwise direction along the boundaries of each room. Subsequently, to ensure that the list represented the relationships between objects, regardless of the starting point, we copied the elements from the front of the list, counting one less than the number of objects found in the image, and added them to the end of the list. If the quantity of elements added to the list exceeded the count of objects identified in the picture minus one, it could potentially result in duplicates during localization. Conversely, if the number of added elements was less than the count of objects identified in the picture minus one, it could lead to potential omissions during localization. Fig. 4 depicts an example. If the cue objects in a room were arranged clockwise as a, b, c, d, and e, the original list was [a, b, c, d, e]. If the image contained three cue objects, additional elements of the list 'a, b', which was one less than the total number of cue objects in the image, were appended at the end of the list, resulting in [a, b, c, d, e, a, b]. Matching parts were then sought between the cue object list created for each room and the list of cue objects present in the image. The matched cue objects were considered candidates for the location from which the photo was taken. For instance, if the cue object list for room A is [a, b, c, d, e, a, b], and the cue object list for the image is [a, b, c], there is one matching object arrangement. Therefore, [a, b, c] inside room A ([**a, b, c**, d, e, a, b]) becomes a candidate location. There could be multiple candidates for each image, or no candidates if the object detection result was incorrect.

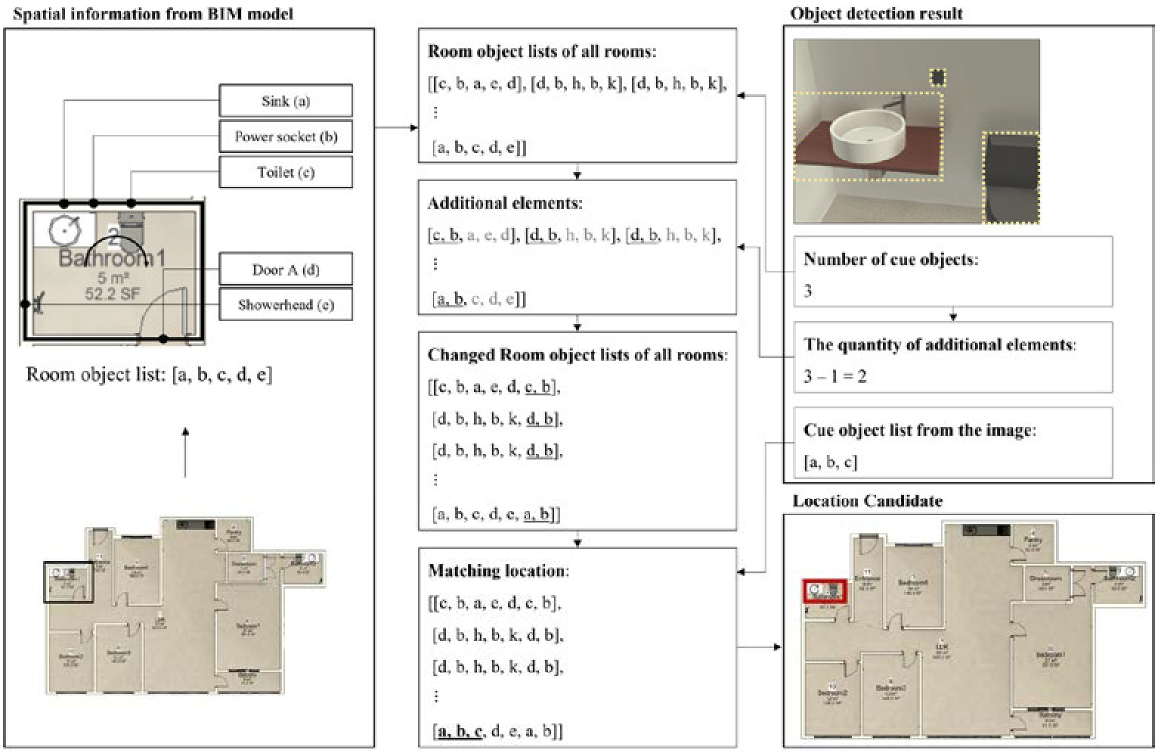

Fig. 4: The process of object location matching

4. RESULTS

4.1 Object Detection

Table 4 presents the model's performance metrics. The object detection model used in the study achieved $mAP_{0.5}$ of 0.9403 and F1 score of 0.9595 (Table 4). Accurate object detection within images certainly resulted in improved performance in subsequent indoor localization tasks because our proposed method relies on the results of object detection; however, the performance tended to degrade exponentially as the number of objects within the images increased as long as the object detection performance reached 100%. The results in Table 4 show that the overall performance decreased, theoretically, by about 6% on average with the addition of each cue object, considering the $mAP_{0.5}$ performance. The proposed localization method also relies on location reasoning, which is positively influenced by increases in cue objects. Thus, the number of cue objects, whether too large or too small, can be detrimental to performance, emphasizing the importance of optimizing the number of cue objects. In addition, Fig. 5 illustrates that the method performed better for objects with less skewness and larger sizes. Due to the presence of only one door B in the BIM model with significant skewness in the image, the accuracy was low for this object. The accuracy for light switches (the smallest of the objects) was slightly lower than for the other objects. Based on the results, it appears that choosing larger cue objects for the localization method would probably have resulted in improved performance.

Table 4: Performance of the object detection model based on the validation dataset

Precision	Recall	F1 score	mAP_0.5
0.9914	0.9295	0.9595	0.9403

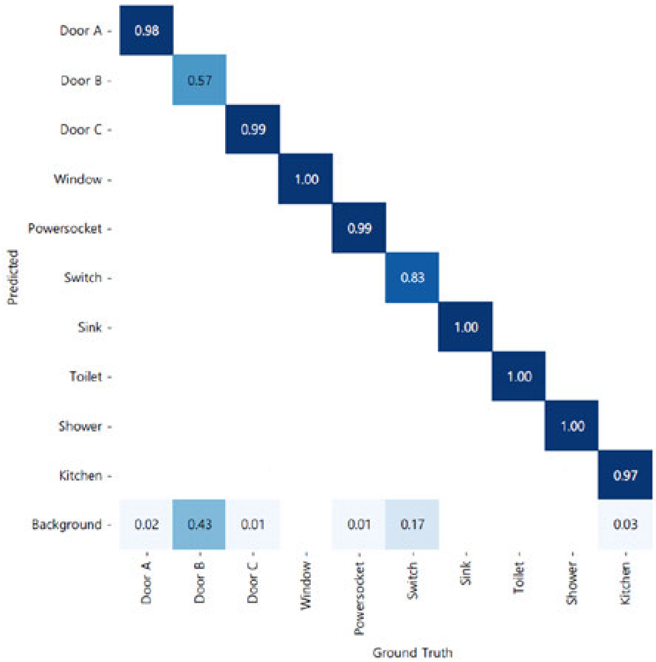

Fig. 5: Confusion matrix for the object detection results

4.2 Optimal Number of Cue Objects

Table 5 shows the evaluation results for the indoor localization method based on object detection and location reasoning for each number of cue objects in the images. Since the first step of the proposed method is to correctly detect every cue object in an image, only cases of every cue object in an image being predicted correctly are considered correct cases. As the number of objects in the image increased, object detection accuracy tended to decrease. This decrease in accuracy was minimal when the number of cue objects (n) changed from 2 (0.88) to 3 (0.80). The magnitude of the decrease was exponential, resulting in an accuracy of 0.20 when $n = 5$. The magnitude of the decrease was more significant than the theoretically estimated 6% decrease for the addition of an object, which was based on the object detection model performance for an individual object.

To identify the correct location among the candidate locations, the object detection results must be accurate. If object detection yields incorrect results, there may be no correct candidates or no candidates present. However, if the object detection results are correct, then at least one of the generated candidates is guaranteed to be correct. Therefore, after performing object detection, we conducted location reasoning for cases where there was a correct candidate and counted the number of generated candidates. Assuming that there was a correct candidate among the generated candidates, we calculated the probability of finding the correct location. However, in cases where the object detection results are wrong, there may be no correct candidate. Therefore, we multiplied the probability of finding the correct location when the correct location was present among the candidates by using object detection accuracy to calculate the probability of locating the correct position using the given method.

We used three metrics to evaluate the performance of the indoor localization method: (A) the mean number of location candidates when the correct location was present among the candidates, (B) the mean probability of finding the correct location when the correct location was present among the candidates, and (C) the mean probability of finding the correct location for both cases when the correct location was present among the candidates and when it was not. The three metrics provided answers to three research questions: (A) How many location candidates will be generated, depending on the number of cue objects? (B) What is the probability of finding the correct location from among the location candidates if the object detection is conducted correctly? (C) What is the probability of finding the correct location with the proposed method, considering both object detection accuracy and the performance of location reasoning. Metric (C) was the primary metric for assessing the model's performance. To compare the performance of the model with and without the influence of object detection, we considered the results based on predicted and actual object information. (A) decreased as the number of cue objects in the image decreased and reached 1.000 when $n = 5$, and (B) could be calculated as the mean value of the inverse of (A), with a higher value indicating better performance. Since (C) considered both the object detection accuracy and the localization reasoning performance, it could be calculated by multiplying the object detection accuracy with (B); hence, a higher value of (C) indicated superior overall model performance.

When cases with correct object detection were considered, the localization performance increased as n increased. However, localization performance did not increase proportionally to n because the accuracy of object detection significantly decreased as n increased. Therefore, when using the predicted object information, the highest performance was observed at $n = 3$, with a probability of 0.283 for finding the correct location. At $n = 4$, the probability of finding the correct location was 0.276, which represented a slight decrease but showed a similar performance to that at $n = 3$. Therefore, even a slight improvement in object detection accuracy for $n = 4$ had the potential to yield a better score than the case at $n = 3$. This result shows that the presence of three to four cue objects in the image yielded optimal results within the given framework.

Table 5: Model evaluation results

Number of cue objects in the image (*n*)	**Object detection accuracy**	**Localization performance based on predicted object information**			**Localization performance based on actual object information**		
		(A)	**(B)**	**(C)**	**(A)**	**(B)**	**(C)**
2	0.88	3.841	0.260	0.229	3.800	0.263	0.263
3	0.80	2.825	0.354	0.283	2.816	0.355	0.355
4	0.52	1.885	0.531	0.276	1.700	0.588	0.588
5	0.20	1.000	1.000	0.200	1.000	1.000	1.000

(A) The mean number of location candidates when the correct location was present among the candidates

(B) The mean probability of finding the correct location when the correct location was included among the candidates.

(C) The mean probability of finding the correct location for both cases when the correct location was present within the candidates and when it was not.

5. CONCLUSION

Many previous studies on indoor localization have been based on the similarities between photos and BIM images. However, these approaches may exhibit weaknesses under varied lighting conditions and with different wallpapers and furniture locations. To overcome these limitations, we propose a reasoning-based approach based on cue objects in photos. With this approach, it is essential to optimize the number of cue objects for detection since it significantly influences performance. Hence, the aim of this preliminary study was to find the optimal number of cue objects in a photo that yielded the best localization performance. The proposed localization method uses spatial information on cue objects detected by a computer vision algorithm to locate shots by analyzing the spatial relationships among the objects found in an image and comparing them with those in the BIM model. We evaluated the method's performance by assessing the probability of accurately determining the location from which a photo was taken, varying the number of cue objects in each photo from two to five.

The experimental results indicated that the model showed the best performance when three cue objects were present in an image. When the number of cue objects increased to four, the probability of accurately determining the exact location decreased slightly compared to the case with three cue objects, mainly due to the dramatic decrease in object detection accuracy. As the number of cue objects captured from the image increased, the number of small and skewed objects also tended to increase, which led to a decrease in overall accuracy. Having a higher number of cue objects can make it easier to deduce the location of a shot accurately, but it may decrease object detection accuracy.

The major contribution of this study lies in suggesting the optimal number of cue objects that should be present in images to determine the locations of photos shot in indoor spaces. This finding highlights the importance of balancing detection performance and reasoning capability in object detection-based indoor localization and considering the number of detected objects. The experimental results provide insights into areas for improvement in future research. First, the method did not perform well when cue-object arrangements in rooms were similar. This limitation could be addressed by considering the size of cue objects and incorporating more diverse spatial information. Second, the error rate accumulated at each stage: the cue-object detection stage, the spatial relationship detection stage, and the location deduction stage. Further research is expected to improve the proposed method to a practically applicable level. The results of this research will be integrated into construction management and maintenance software, enabling the automatic tagging of locations in provided images.

6. ACKNOWLEDGEMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2021R1A2C3008209).

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INTEGRATING GREEN ROOFS INTO BUILDING INFORMATION MODELING (BIM): A COMPUTATIONAL APPROACH FOR SUSTAINABLE BUILDING DESIGN

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ABSTRACT: *The construction industry is currently witnessing a transformative period characterized by the convergence of the green and digital transitions. The green transition seeks to address environmental challenges such as climate change and resource depletion, while the digital transition leverages advanced technologies to enhance construction processes. This paper specifically explores the integration of green roofs, as component of sustainable buildings, into the Building Information Modeling (BIM) framework, a key enabler of the digital transition. Green roofs, known for their environmental benefits, consist of layers that contribute to energy efficiency, stormwater management, and biodiversity enhancement. To optimize their design and performance, this research employs Dynamo Visual Programming Language (VPL) within Autodesk Revit to create parametric models of green roofs. These models facilitate the evaluation of thermal and structural characteristics under varying water content conditions (dry and saturated). Results reveal that the choice of substrate and drainage materials significantly impacts thermal resistance, particularly in dry conditions. However, in saturated conditions, the influence on thermal performance converges, emphasizing the importance of structural considerations in both scenarios. The research also highlights various limitations and outlines avenues for future studies, including expanding the range of materials, exploring additional performance metrics, and incorporating AI and machine learning techniques. By addressing these aspects, this research contributes to a comprehensive understanding of the integration of green roofs and BIM. It provides designers and researchers with a practical tool for optimizing green roof designs, aligning with contemporary sustainable construction practices, and promoting the holistic development of green buildings.*

KEYWORDS: *Sustainability integration; Parametric modeling; Digital Transformation*

1. INTRODUCTION

The construction sector is currently undergoing significant transformations driven by the green and digital transitions. The green transition refers to the shift towards sustainable practices and environmentally friendly solutions within the industry (Mina et al., 2021). This transition is motivated by the urgent need to address climate change, resource depletion, and environmental degradation (Bherwani et al., 2022). As a result, the construction sector is increasingly adopting strategies and technologies that reduce the environmental impact of buildings and infrastructure. Simultaneously, the digital transition has brought about a profound change in the construction industry, fueled by the rapid advancements in digital technologies (Huang et al., 2021). This transition involves the integration of digital tools, processes, and data management systems to improve efficiency, productivity, and collaboration across all stages of the building life cycle (Giovanardi et al., 2023). Building Information Modeling (BIM) has emerged as a key component of the digital transition, revolutionizing the way information is shared, analyzed, and utilized within the construction industry.

Among the various components employed in green buildings, green roofs have gained recognition as an effective technological solution for improving sustainability and the life cycle performance of buildings (S. Cascone, 2022). A green roof, also known as a living roof or vegetated roof, refers to a roofing system that incorporates vegetation, growing medium, and waterproofing layers (Vijayaraghavan, 2016). It offers numerous environmental, social, and economic benefits, making it an integral part of green building practices (Shafique et al., 2020). Each layer of the green roof system works in tandem to provide a range of benefits. The waterproofing layer ensures the building's protection, while the root barrier prevents potential damage. The drainage layer manages stormwater, preventing flooding and alleviating pressure on drainage infrastructure. The growing medium layer supports plant growth by providing adequate nutrients and moisture retention. Finally, the vegetation layer enhances biodiversity, improves air quality, reduces energy consumption, and mitigates the environmental impact of the building.

The digital transition has ushered in a new era of possibilities and advancements in the construction industry, necessitating the adoption of digital tools and processes to optimize project outcomes (Mehrbod et al., 2019). At the forefront of this transition is Building Information Modeling (BIM), a powerful technology that revolutionizes the way information is managed, shared, and utilized throughout the building life cycle (Wang et al., 2019). BIM

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Stefano Cascone, *Integrating Green Roofs into Building Information Modeling (BIM): A Computational Approach for Sustainable Building Design*, pp. 988-997, DOI 10.36253/979-12-215-0289-3.99

is a collaborative process that involves creating and managing digital representations of physical and functional characteristics of a building. It enables stakeholders, including architects, engineers, contractors, and facility managers, to work together in a coordinated manner, streamlining communication and enhancing decision-making. BIM serves as a digital repository of information, encompassing 3D models, 2D drawings, specifications, schedules, and other pertinent data related to the building (Gimenez et al., 2015).

One of the key advantages of BIM lies in its ability to support the supply, integration, and management of information throughout the entire life cycle of a building (Alireza et al., 2017). During the design phase, BIM facilitates the creation of detailed 3D models that allow for visualization, clash detection, and simulation of various design scenarios. Therefore, to fully capitalize on the advantages of green roofs, the integration of these systems with BIM is of utmost importance. Previous research (Korol et al., 2019) discussed the integration between green roof and BIM technologies used in the engineering design of such systems. This previous research explained that to create a BIM object of an extensive green roof system, complex programs such as AECOsim, ARCHICAD, IFC, Revit, and Vectorworks are needed. The authors also mentioned that the NBS National BIM Library in the UK sets an industry standard for quality, efficient generic and manufacturers' objects, including green roof systems. However, they did not provide detailed information on the integration process between green roof and BIM. Other authors (Yu et al., 2017) discussed the application of BIM in the case study of green roof innovation. Specifically, the authors incorporated BIM and energy consumption analysis software to demonstrate the benefits of the proposed eco-innovative green roof alternative. Finally, in a further study (Kasmion et al., 2000) reported on a simulation study using Autodesk Revit BIM software to investigate how types of roof design and green roof application may reflect on container's heat absorption. This study found that a curved roof surface with green roof produces a better heat absorption quality.

While there is a growing recognition of the benefits of green roofs and the potential of BIM in the construction industry, there is a notable gap in research that specifically explores the integration of these two domains. The gap in scientific knowledge lies in the lack of established frameworks, guidelines, and best practices for effectively integrating green roofs within the BIM environment. There is limited research that examines the specific workflows, data management strategies, and computational automation techniques required to successfully incorporate green roofs into the BIM framework. Furthermore, the understanding of how green roof components, materials, and performance characteristics can be accurately represented and analyzed within the BIM environment is also lacking.

In this paper, the focus lies in studying the integration methods between green buildings and BIM, specifically emphasizing the incorporation of green roofs. Green roofs, also comprising innovative components and products, such as recycled polyethylene, offer unique opportunities to enhance the sustainability of buildings. To achieve this integration, the Dynamo Visual Programming Language (VPL) workflow within Autodesk Revit, the most widely used BIM authoring software, was employed. Dynamo enabled computational automation, allowing for the development of parametric and informative models of green roofs. These models provided computational automation for determining the thermal and structural characteristics of the different green roof technologies in different water content conditions (dry and saturated) that can be used for controlling and coordinating the entire life cycle of a green roof, especially during the initial design stage.

This research aims to contribute to a deeper understanding of how the combined power of green building practices and BIM technology can foster sustainable development in the construction sector.

2. MATERIALS AND METHODS

The research is focused on investigating the integration methods between green buildings and Building Information Modeling (BIM), with a specific emphasis on the incorporation of green roofs, and it involves the computational modelling using the Dynamo Visual Programming Language (VPL) workflow within Autodesk Revit. The parametric models enable the manipulation of design parameters, such as green roof technologies and water content conditions (dry and saturated), to assess their impact on thermal and structural characteristics.

2.1. Green roof technologies

The material characteristics of the drainage layer and substrate in green roofs were evaluated through previous experimental studies. Three types of drainage layers and substrates were considered in this study. In terms of the drainage layers, commercially available granular products such as perlite and expanded clay were examined. Additionally, previous research proposed recycled polyethylene as a potential drainage layer for green roofs, aiming to enhance sustainability while reducing environmental and economic impacts associated with production and transportation.

Regarding the substrates, three different compositions were investigated. Substrate S1 consisted of lapilli, pumice, zeolites, peat, and slow-release fertilizers. Substrate S2 comprised a mixture of mineral volcanic materials combined with organic substances, while Substrate S3 was formulated with a higher percentage of organic matter compared to the other substrates to increase water retention. It was also composed of locally available materials.

Following laboratory tests conducted in previous research, the thermal and physical characteristics of the materials used for both the drainage layer and substrate were considered under dry and saturated conditions. In a green roof system, saturated conditions are reached after a rain or irrigation event, while dry conditions are obtained when the water has completely evaporated during prolonged droughts. As evidenced by Table 1 and Table 2, altering the water content in the materials resulted in changes to their thermal and physical properties.

These evaluations provide valuable insights into the performance of drainage layer and substrate materials, offering a comprehensive understanding of their behavior under different water content conditions. This knowledge is essential for optimizing the design and performance of green roofs, enabling informed decision-making and promoting sustainable practices within the construction industry.

Table 1: Thermal and physical properties for drainage layer materials (Cascone & Gagliano, 2022).

	Dry conditions		**Saturated conditions**	
	Thermal conductivity [W/mK]	Density [kg/m3]	Thermal conductivity [W/mK]	Density [kg/m3]
Perlite	0.076	164.2	0.312	510.5
Expanded clay	0.124	410.4	0.234	579.3
Recycled polyethylene	0.098	329.4	0.144	411.7

Table 2: Thermal and physical properties for substrate materials (S. Cascone & Gagliano, 2023).

	Dry conditions		**Saturated conditions**	
	Thermal conductivity [W/mK]	Density [kg/m3]	Thermal conductivity [W/mK]	Density [kg/m3]
Substrate S1	0.113	1000.2	0.463	1355.5
Substrate S2	0.134	919.4	0.458	1358.4
Substrate S3	0.084	605.4	0.418	1183.9

2.2. Computational modelling with Dynamo Visual Programming Language (VPL)

To achieve the integration of green buildings and Building Information Modeling (BIM), the research employs the Dynamo Visual Programming Language (VPL) as a key tool within Autodesk Revit. Dynamo VPL enables computational automation and facilitates the development of parametric and informative models specifically tailored to green roofs.

The initial step involved modeling the materials utilized for green roof layers within the Dynamo environment. This was accomplished by duplicating existing materials from the Revit Material's Asset and renaming them using custom nodes based on Python scripts previously developed within Dynamo. This approach was necessary as standard nodes do not directly manipulate the Revit Material's Asset.

The "Thermal conductivity" and "Density" nodes provide the property values under both dry and saturated conditions, as indicated in Table 1 and Table 2 (Fig. 1 depicts the Dynamo workflow for creating the perlite drainage material). The "If" node automatically switches the thermal conductivity and density values between dry and saturated conditions. In this research, "true" represents dry conditions and "false" represents saturated conditions. For example, in the case of perlite, when the water condition is set to dry, the thermal conductivity is

0.076 W/mK and the density is 164.2 kg/m^3. Conversely, when the water condition is set to saturated, the thermal conductivity becomes 0.312 W/mK and the density changes to 510.5 kg/m^3.

This aspect of the workflow is particularly noteworthy as it enables the computational automation of thermal and physical properties for green roofs during the design stage, depending on the water content. With just a single click, users can assess the thermal and physical performance of green roofs under dry or saturated conditions, as described later in the research.

The "Material.SetThermal" node is responsible for creating new materials, such as "Perlite" in Fig. 1, with properties defined in "Thermal.SetProperties" that vary based on the input from the "True/False" node positioned at the beginning of the workflow.

The workflow illustrated in Fig. 1 for creating perlite serves as the basis for generating the other drainage and substrate materials. Fig. 2 showcases the workflow with all the materials created. All the "Thermal conductivity" and "Density" nodes are connected to the same "True/False" (dry/saturated) node, ensuring the water content condition is automatically considered.

2.3. Thermal and structural characteristics

The first step involves assigning the green roof materials to the "Green roof" type, which consists of two layers: one for the substrate and another for the drainage layer. The impact of waterproof and anti-root membranes, as well as the filter layer, on the thermal and structural characteristics of the green roof is negligible and, therefore, not considered.

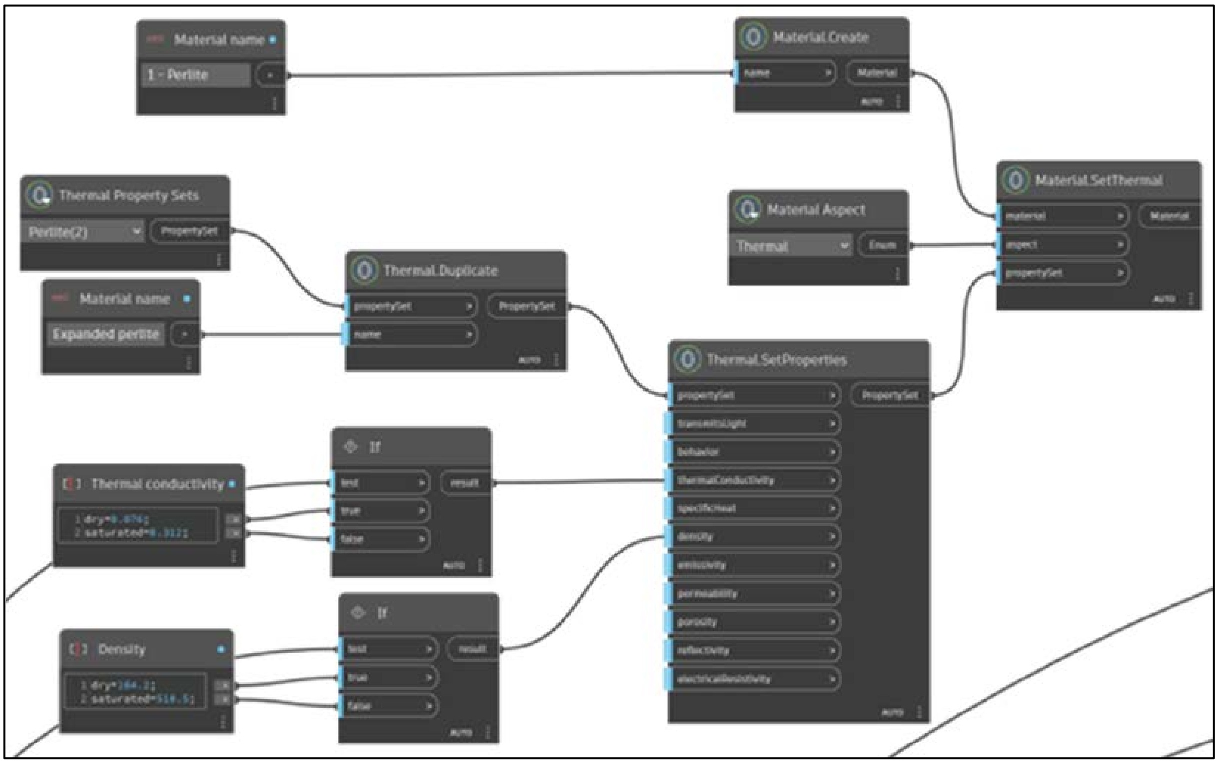

Fig. 1: Material creation in Revit by using Dynamo workflow.

To facilitate the evaluation of the thermal and structural characteristics of the green roof, custom nodes were developed (Fig. 3). The "Index" parameter indicates the layer position, with "0" representing the substrate (upper layer) and "1" representing the drainage layer (lower layer). Since the thickness of the materials plays a crucial role in determining the performance of the green roof, the workflow incorporates a component that automatically adjusts the material thicknesses.

Given the focus on extensive green roofs in this research, the substrate thickness varies between 10 cm and 20 cm, while the drainage layer thickness ranges from 4 cm to 6 cm. As an average value, a substrate thickness of 15 cm and a drainage layer thickness of 5 cm were adopted.

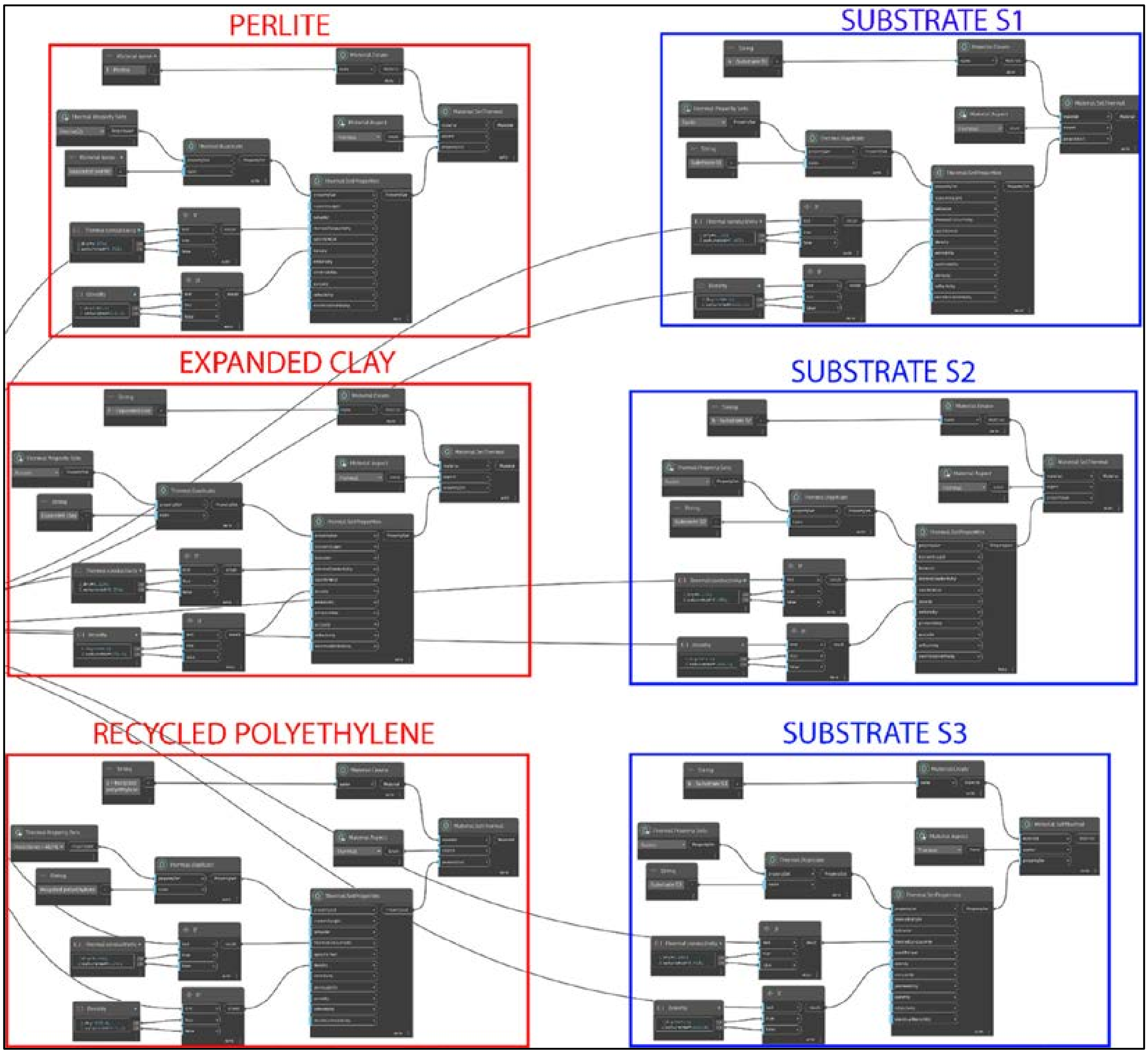

Fig. 2: Material creation for drainage layers (in red) and substrates (in blue).

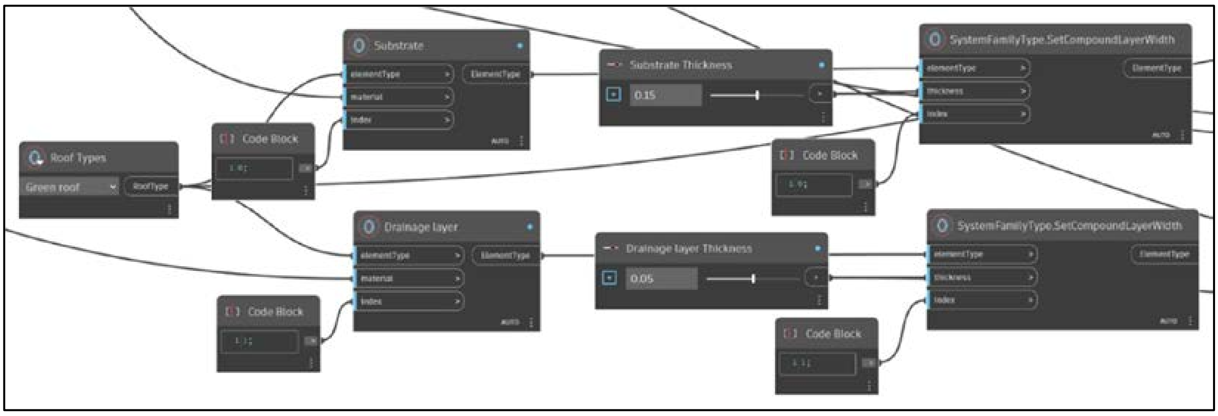

Fig. 3: Layer creation into the green roof type and parametric thickness modelling.

By selecting the appropriate materials within the "Substrate" and "Drainage layer" nodes, the new materials are automatically assigned to the Revit model, ensuring seamless integration and representation of the green roof components.

Finally, Fig. 4 illustrates the workflow employed to evaluate the thermal and structural characteristics of green roofs. In terms of thermal performance, the thermal resistance was a key factor considered. This property was automatically measured by Revit and imported into Dynamo, considering the thermal conductivities of the various substrate and drainage materials, which are influenced by the water content conditions (dry or saturated), as well as the material thicknesses.

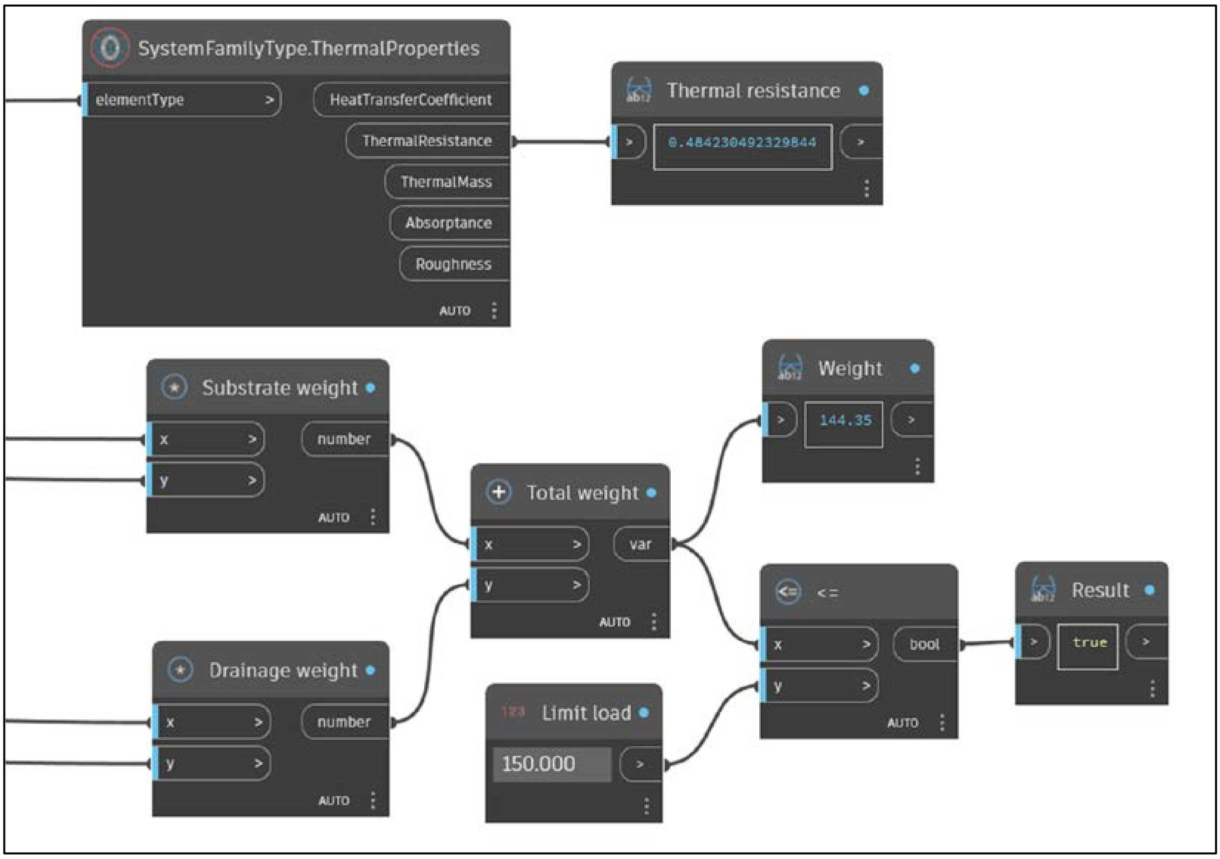

Fig. 4: Thermal and structural characteristics of green roof evaluation.

Regarding the structural performance, the weight of the different green roof configurations was determined. The total weight depends on the density of the substrate and drainage layers, which are also influenced by the water content conditions and the material thicknesses. By multiplying the density of the materials by their respective thicknesses, the total weight of each green roof configuration was calculated.

According to the European standard, if a roof is intended to be walkable during the design stage, it should be able to withstand a maximum load of 200 kg/m^2. The total weight of the different green roof solutions was compared to this limit to assess their compatibility with existing buildings, aiming to avoid costly structural modifications.

By considering both the thermal and structural characteristics aspects, this workflow provides valuable insights into the suitability of different green roof options, facilitating informed decision-making during the design stage. It enables designers and researchers to assess the thermal efficiency and structural integrity of green roofs, ensuring their compatibility with existing building structures and meeting the required standards.

3. RESULTS AND DISCUSSION

Table 3 and Table 4 present the results for green roofs in dry and saturated conditions, respectively. In terms of thermal resistance in dry conditions, the highest performance was observed when combining Substrate S3 with perlite (2.44 m2K/W), while the lowest performance was measured when Substrate S2 was coupled with expanded clay (1.52 m2K/W). These results highlight the significant impact of substrate and drainage material combinations on the thermal performance of green roofs in dry conditions. Therefore, in dry conditions, the materials tested have similar thermal performance of 3-cm insulation materials.

Table 3: Thermal and structural characteristics in dry condition.

	Perlite		Expanded clay		Recycled polyethylene	
	Thermal Resistance [m^2K/W]	Weight [kg/m^2]	Thermal Resistance [m^2K/W]	Weight [kg/m^2]	Thermal Resistance [m^2K/W]	Weight [kg/m^2]
Substrate S1	1.99	158.2	1.73	170.5	1.84	166.5
Substrate S2	1.78	146.1	1.52	158.4	1.63	154.4
Substrate S3	2.44	99.0	2.19	111.3	2.30	107.3

Table 4: Thermal and structural characteristics in saturated condition.

	Perlite		Expanded clay		Recycled polyethylene	
	Thermal Resistance [m2K/W]	Weight [kg/m2]	Thermal Resistance [m2K/W]	Weight [kg/m2]	Thermal Resistance [m2K/W]	Weight [kg/m2]
Substrate S1	0.48	228.8	0.54	232.3	0.67	223.9
Substrate S2	0.49	229.3	0.54	232.7	0.67	224.3
Substrate S3	0.52	203.1	0.57	206.6	0.71	198.2

In saturated conditions, the thermal resistance decreased due to the higher thermal conductivity of water. As a result, the thermal performance of different green roofs became similar, with an average value of 0.55 m2K/W. These findings indicate that under saturated conditions, the thermal performance of green roofs is less influenced by the specific substrate and drainage material combinations and tends to converge to a similar performance level across the tested variants. This resistance value is close to the one measured for natural materials, such as wood, straw, etc. Designers can consider these average values during the design stage to estimate the energy performance of green roofs in terms of energy consumption.

Regarding the structural performance, all green roof configurations exhibited weights lower than the imposed limit overload of 200 kg/m2 in dry conditions, with the lighter solution being the Substrate S3, due to its composition, when coupled with perlite as drainage layer. The heaviest solution is the Substrate S1 in combination with expanded clay. However, in saturated conditions, only when Substrate S3 was coupled with recycled polyethylene as drainage materials, the weight remained below the limit overload due to hygroscopic structure of the granular materials used for the green roof. In fact, the recycled plastic does not absorb water differently from perlite and expanded clay. This finding is significant, particularly for the retrofitting of existing buildings, as it highlights the importance of considering the structural performance of green roofs not only in dry conditions, as is often the case, but also in saturated conditions.

The workflow created using Dynamo within Revit proved to be effective in automating the determination of thermal and structural characteristics of green roofs during the design stage. This automation allowed for seamless transition between dry and saturated conditions by adjusting the material properties accordingly. The ability to rapidly assess these characteristics enables designers to make informed decisions during the early design stage.

Designers can employ the algorithm to explore various green roof configurations and materials, considering both thermal resistance and structural weight. By inputting different parameters into the Dynamo workflow, such as substrate types and drainage materials, designers can optimize green roof designs for specific project requirements. For instance, if the primary goal is to maximize thermal resistance while keeping structural weight within a certain limit, the algorithm can assist in identifying the most suitable combinations of materials.

Furthermore, the algorithm's flexibility extends to various climate conditions and building types. Designers can use it to assess the performance of green roofs in different regions, taking into account variations in temperature, precipitation, and structural load requirements. This adaptability empowers architects and engineers to tailor green roof designs to meet energy efficiency goals and structural integrity standards in diverse contexts.

Overall, the results demonstrate the importance of considering both thermal and structural characteristics of green roofs, not only in dry conditions but also in saturated conditions. The integration of the developed workflow using Dynamo and Revit provides a practical and efficient means to assess and compare the performance of green roof options, facilitating informed decision-making during the design stage. These findings contribute to the understanding and optimization of green roof designs in terms of energy consumption and structural integrity.

By incorporating this algorithm into the design process, architects and engineers can enhance the sustainability of buildings by leveraging green roofs as energy-efficient and structurally viable components. This technology-driven approach aligns with contemporary design practices that prioritize eco-friendly solutions while maintaining building performance standards.

4. LIMITATIONS AND FUTURE DEVELOPMENTS

This section outlines the limitations of the current study and presents directions for future research to address these limitations.

Future research should include real-world case studies to provide a more concrete understanding of the algorithm's practical use and effectiveness. These case studies can demonstrate how the Dynamo Visual Programming Language (VPL) workflow within Autodesk Revit can be effectively applied to model green roofs in various construction projects, thus contextualizing the algorithm within practical design scenarios.

The analysis in the current study primarily focused on thermal resistance and structural weight as key performance metrics. However, a broader range of performance indicators, including water retention, stormwater management, biodiversity enhancement, and acoustics, should be explored in future research. This will enable a more comprehensive evaluation of green roof performance, considering their contributions to sustainable construction from multiple angles.

While the current research addressed the design phase of green roofs and their integration with BIM, it did not extensively explore the construction and maintenance phases. Future research should encompass these phases to gain a holistic understanding of green roofs' performance, durability, and maintenance requirements throughout the entire building lifecycle.

To ensure the robustness and adaptability of the methodology, future research should consider alternative methodologies and tools. This diversification will accommodate different research questions and potential variations in results. Additionally, exploring interoperability with other BIM software platforms will enhance the methodology's relevance and applicability.

Integration of artificial intelligence (AI) and machine learning techniques within the BIM environment should be explored in future research. This will enable the optimization of green roof designs, prediction of performance outcomes, and data-driven recommendations for materials and configurations, aligning the work with emerging trends in construction technology.

Future research should involve the development of standardized guidelines and protocols for integrating green roofs within the BIM framework. These guidelines can streamline data exchange, model interoperability, and collaboration among stakeholders, promoting efficient and consistent implementation of green roof projects. Additionally, analyzing the economic aspects, including life cycle costs, return on investment, and financial incentives, should be a focus. Assessing the economic benefits of green roofs in terms of energy savings, improved building performance, and increased property value will provide valuable insights for decision-makers.

To promote holistic and integrated sustainable building solutions, collaborative research efforts should be initiated to explore potential synergies between green roofs and other sustainable building strategies, such as renewable energy systems, water conservation measures, and smart technologies. Integrating these strategies within the BIM framework will contribute to a more comprehensive approach to sustainable construction, thereby addressing the de-contextualization issue raised by the reviewer.

Incorporating these considerations into future research agendas will provide a more comprehensive and contextualized view of the integration of green roofs and BIM, addressing the reviewer's concerns and enhancing the practicality and relevance of the work.

5. CONCLUSIONS

In conclusion, this research contributes to a deeper understanding of the integration methods between green buildings and Building Information Modeling (BIM), with a specific focus on the incorporation of green roofs. By employing the Dynamo Visual Programming Language (VPL) workflow within Autodesk Revit, computational automation was achieved, enabling the development of parametric and informative models of green roofs.

The analysis in dry and saturated conditions provided valuable insights into the thermal and structural characteristics of different green roof technologies. The findings highlight the importance of substrate and drainage material combinations in influencing thermal resistance in dry conditions, as well as the significance of considering structural performance in both dry and saturated conditions.

However, it is important to acknowledge the limitations of this research, including the specific focus on certain green roof technologies, the limited scope of performance metrics, and the emphasis on the design stage. Future developments can address these limitations and further advance the integration of green buildings and BIM:

- Exploring a wider range of green roof technologies and materials.
- Investigating additional performance metrics related to water retention, stormwater management, biodiversity enhancement, and acoustics.
- Extending the research to include the construction and maintenance phases.
- Considering alternative methodologies and software tools.
- Integrating artificial intelligence and machine learning techniques, developing standardized guidelines, assessing the economic aspects, and exploring synergies with other sustainable building strategies.

By addressing these limitations and pursuing future developments, the integration of green buildings and BIM can be further optimized, contributing to the advancement of sustainable development in the construction sector.

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ENHANCING DISASTER RESILIENCE STUDIES: LEVERAGING LINKED DATA AND NATURAL LANGUAGE PROCESSING FOR CONSISTENT OPEN-ENDED INTERVIEWS

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ABSTRACT: *Researchers have long focused on disaster resilience to mitigate calamity disruption. Disaster resilience is a complex and multi-faceted concept that is challenging to measure. Quantitative methods have traditionally been used to assess disaster resilience, but a growing interest in qualitative methods like open-ended interviews has emerged to understand experiences and perspectives. To gain deep and consistent knowledge, an open-ended interview should focus on an interviewee's point of view and ask follow-up questions from a knowledge base that consists of relevant information; otherwise, this can lead an open-ended interview to deviate from the interviewee's point of view to the interviewer's point of view. In contrast to what is desired, individual interviews with last year's students in the field of civil engineering with a predefined and limited knowledge base demonstrated inconsistency in asking a follow-up question from an already existing open-ended interview. To tackle this gap, firstly, we suggest a knowledge base that can be built from peer-reviewed papers published in the disaster resilience field; secondly, we suggest a Natural Language Processing based Decision Support System using Sentence Embedding that can analyze the interviewee's response and find resources from the knowledge base to assist the interviewer in making a consistent follow-up question.*

KEYWORDS: *Disaster resilience; Decision support systems; Open-ended interviews; Knowledge management; NLP*

1. INTRODUCTION

Disaster resilience is a critical aspect of construction technology that plays a pivotal role in mitigating the impacts of various natural and human-induced hazards on built infrastructure (Malalgoda, Amaratunga, & Haigh, 2014). In recent years, there has been an increasing emphasis on enhancing disaster resilience in the construction industry due to the rising frequency and intensity of disasters worldwide (Harrison & Williams, 2016). Ensuring the resilience of constructed facilities not only safeguards public safety but also minimizes economic losses and facilitates rapid recovery in the aftermath of disruptive events (Ouyang, Dueñas-Osorio, & Min, 2012).

The challenges posed by disasters necessitate a comprehensive understanding of the factors influencing resilience in the context of construction projects. Traditional research methodologies, such as closed-ended interviews and surveys, have been instrumental in gathering valuable data on disaster resilience (Cai et al., 2018). However, these methods often fall short in capturing the full depth of participants' experiences and viewpoints, leading to potential biases in data collection.

The specific research objectives of this paper are as follows:

1. To investigate the impact of consistency in open-ended interviews on disaster resilience measurement within the disaster resilience domain.
2. To develop and implement advanced Natural Language Processing (NLP) based Decision Support System (DSS) with sentence embedding techniques to enhance data collection in open-ended interviews.
3. To create a knowledge base that aggregates and organizes peer-reviewed papers and experts' insights related to disaster resilience in construction projects.

The research questions guiding this study are:

Research Question 1: How does consistency in open-ended interviews influence the reliability and depth of data collected for disaster resilience measurement in construction technology?

Referee List (DOI: 10.36253/fup_referee_list)
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Milad Katebi, Mani Poshdar, Mostafa Babaeian Jelodar, Morteza Zihayat, *Enhancing Disaster Resilience Studies: Leveraging Linked Data and Natural Language Processing for Consistent Open-Ended Interviews,* pp. 998-1009, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.100

Research Question 2: Can leveraging NLP and sentence embedding techniques enhance the contextual relevance of follow-up questions in open-ended interviews within the construction technology domain?

Research Question 3: How does the proposed decision support system, empowered by the knowledge base, improve data collection and analysis in open-ended interviews on disaster resilience in construction projects?

This paper addresses the significance of consistency in open-ended interviews concerning disaster resilience measurement within the domain of construction technology. We recognize the limitations of conventional interview techniques and aim to enhance data collection by leveraging advanced NLP and sentence embedding techniques. By utilizing a knowledge base of relevant topics in the field of disaster resilience, our proposed approach generates contextually relevant follow-up questions that align more closely with the interviewee's point of view.

The contributions of this work are threefold. In this research, first, we demonstrate the existent level of inconsistency in disaster resilience measurement domain. Next, we introduce a knowledge base that aggregates and organizes peer-reviewed papers and experts' insights in the mentioned domain. This knowledge base empowers our decision support system to identify and generate pertinent follow-up questions for interviewees, facilitating a more nuanced understanding of their perspectives. Last, we leverage state-of-the-art NLP and sentence embedding techniques to ensure the semantic similarity between the interview responses and the knowledge base, enabling a more accurate assessment of disaster resilience.

Using a decision support system is one method of reducing cognitive errors. To help people with complicated decision-making tasks, DSSs offer tools and cognitive aids, minimizing reliance on memory and cognitive processes alone (Arnott, 2006). DSS assists people in avoiding biases, mistakes, and oversights that may result from impaired cognitive function or flawed heuristics by offloading cognitive burden and offering organized advice. Such decision support systems can be implemented and used to improve human performance and decision outcomes in a variety of domains.

In the following sections, we detail our methodology, including the data collection process, the implementation of sentence embedding and NLP algorithms, and the evaluation of our decision support system. We also present the results of our experiments and discuss their implications for the construction technology field. Ultimately, we believe that our approach holds great promise in improving the consistency and depth of data collected from open-ended interviews, thereby advancing the measurement, and understanding of disaster resilience in construction projects.

2. LITERATURE REVIEW

As discussed, interviews serve as the primary data gathering method for disaster resilience measurement. Moreover, open-ended interviews offer valuable insights into individuals' perspectives; however, the variation in follow-up questions among different interviewers can lead to inconsistency and reduced reliability of data gathered. This section examines the focus of existing solutions in various domains, particularly in healthcare, where NLP has been applied to assist in decision-making processes. Additionally, the lack of existing any DSS that utilizes NLP to aid in interview processes within the domain of disaster resilience will be highlighted.

The literature review section follows a systematic literature review process as described by (Y. Xiao & Watson, 2019), with step-by-step details presented in Fig. 1. The literature review commenced by defining a set of keywords, namely (NLP OR (natural AND language AND processing)) AND (dss OR (decision AND support AND system*)) AND interview to cover the scope of our research. Wildcard characters and special terms were employed to identify relevant papers. The keywords were used to search in the abstract, keywords and titles of peer-reviewed papers. The search yielded 32, 8, 3, and 11 papers from Scopus, IEEE, ScienceDirect, and PubMed databases, resulting in a total of 54 papers. By following Fig. 1, the reasoning and numbers of each step is discussed.

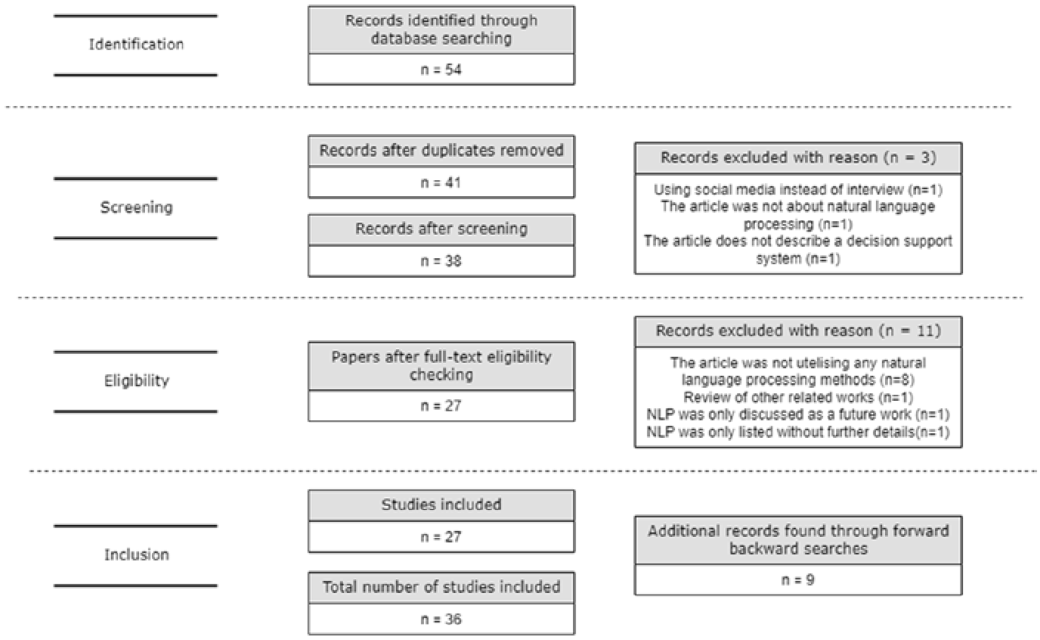

Fig. 1: Literature review's strategy applied by following Xiao's systematic literature review process (Xiao and Watson 2019).

The list of selected papers, along with their domain classifications, is presented in Table 1. The classification was done by finding relevant keywords to a specific field that an NLP based DSS was designed for. The classification categories included healthcare, engineering, HR, law, and business domains. Healthcare classification was related to any health-related papers and engineering ones were the papers mostly focusing on engineering fields like mechanical engineering, constructions, and related topics. Any paper within the concept of law, court, and advocacy sat within the classification of law leaving HR related ones for hiring related topics and the only business one addressing an NLP based DSS within an enterprise.

Table 1: List of selected papers from systematic literature review.

Author and Year	Title	Domain
(Bazzan, Echeveste, Formoso, Altenbernd, & Barbian, 2023)	An Information Management Model for Addressing Residents' Complaints through Artificial Intelligence Techniques.	Engineering
(Afshar et al., 2023)	Deployment of Real-time Natural Language Processing and Deep Learning Clinical Decision Support in the Electronic Health Record: Pipeline Implementation for an Opioid Misuse Screener in Hospitalized Adults.	Healthcare
(Sultanum, Naeem, Brudno, & Chevalier, 2022)	ChartWalk: Navigating large collections of text notes in electronic health records for clinical chart review.	Healthcare
(Yadav & Sharma, 2023)	A novel automated depression detection technique using text transcript.	Healthcare
(Lau, Zhu, & Chan, 2023)	Automatic depression severity assessment with deep learning using parameter-efficient tuning.	Healthcare
(Huang, Liu, & Lee, 2023)	Talent recommendation based on attentive deep neural network and implicit relationships of resumes.	HR
(J. Wang et al., 2022)	PhenoPad: Building AI enabled note-taking interfaces for patient encounters.	Healthcare
(Chaichulee et al., 2022)	Multi-label classification of symptom terms from free-text bilingual adverse drug reaction reports using natural language processing.	Healthcare
(Fujimori et al., 2022)	Acceptance, Barriers, and Facilitators to Implementing Artificial Intelligence–Based Decision Support Systems in Emergency Departments: Quantitative	Healthcare

	and Qualitative Evaluation.	
(Barale, 2022)	Human-Centered Computing in Legal NLP An Application to Refugee Status Determination.	Law
(Rachana, Vishwas, & Priyanka, 2022)	HR based Chatbot using Deep Neural Network.	HR
(C. Wang et al., 2022)	A Multi-modal Feature Layer Fusion Model for Assessment of Depression Based on Attention Mechanisms.	Healthcare
(Flores, Tlachac, Toto, & Rundensteiner, 2022b)	Transfer learning for depression screening from follow-up clinical interview questions.	Healthcare
(Flores, Tlachac, Toto, & Rundensteiner, 2022a)	AudiFace: Multimodal Deep Learning for Depression Screening.	Healthcare
(X. Yang, Joukova, Ayanso, & Zihayat, 2022)	Social influence-based contrast language analysis framework for clinical decision support systems.	Healthcare
(Jan et al., 2021)	The role of machine learning in diagnosing bipolar disorder: Scoping review.	Healthcare
(Jenkins et al., 2021)	User testing of a diagnostic decision support system with machine-Assisted chart review to facilitate clinical genomic diagnosis.	Healthcare
(Barr et al., 2021)	An Audio Personal Health Library of Clinic Visit Recordings for Patients and Their Caregivers (HealthPAL): User-Centered Design Approach.	Healthcare
(Toto, Tlachac, & Rundensteiner, 2021)	Audibert: A deep transfer learning multimodal classification framework for depression screening.	Healthcare
(Ivanchikj, Serbout, & Pautasso, 2020)	From text to visual BPMN process models: Design and evaluation.	Business
(Uttarwar, Gambani, Thakkar, & Mulla, 2020)	Artificial intelligence based system for preliminary rounds of recruitment process.	HR
(Bautista, Aló, & Wang, 2020)	Deep Learning, Cloud Computing for Credit/Debit Industry Analysis of Consumer Behavior.	Law
(Z. Xiao, Zhou, Chen, Yang, & Chi, 2020)	If I hear you correctly: Building and evaluating interview chatbots with active listening skills.	HR
(Berquand et al., 2019)	Artificial Intelligence for the Early Design Phases of Space Missions.	Engineering
(Mai et al., 2018)	Modeling Security and Privacy Requirements: a Use Case-Driven Approach.	Law
(Kramer & Drews, 2017)	Checking the lists: A systematic review of electronic checklist use in health care.	Healthcare
(Saloun, Ondrejka, Malčík, & Zelinka, 2016)	Personality disorders identification in written texts.	Healthcare
(Højen, Elberga, & Andersena, 2014)	SNOMED CT adoption in Denmark-why is it so hard?	Healthcare
(Ku & Leroy, 2014)	A decision support system: Automated crime report analysis and classification for e-government.	Law
(Bagheri, Ensan, & Gasevic, 2012)	Decision support for the software product line domain engineering lifecycle.	Engineering
(Huang et al., 2011)	Lessons learned in improving the adoption of a real-time NLP decision	Healthcare

	support system.	
(Santelices et al., 2010)	Development of a hybrid decision support model for optimal ventricular assist device weaning.	Healthcare
(Young et al., 2007)	Runtime application of Hybrid-Asbru clinical guidelines.	Healthcare
(Sharda, Das, Cohen, & Patel, 2006)	Customizing clinical narratives for the electronic medical record interface using cognitive methods.	Healthcare
(Warren, 1998)	Better, more cost-effective intake interviews.	Healthcare
(Warren, Warren, & Freedman, 1994)	Interviewing expertise in primary care medicine: A knowledge-based support system.	Healthcare

Fig. 2 illustrates the distribution of covered domains, with healthcare prominently represented. While other domains are gaining attention, healthcare remains the dominant focus in NLP-based DSS research. Of particular significance, the inclusion of disaster-related keywords in our search strategy consistently yielded zero papers, underscoring the absence of NLP-based DSS designed for disaster-related open-ended interviews. Hence, this paper addresses the imperative need for such a system and provides a solution to bridge this gap in research.

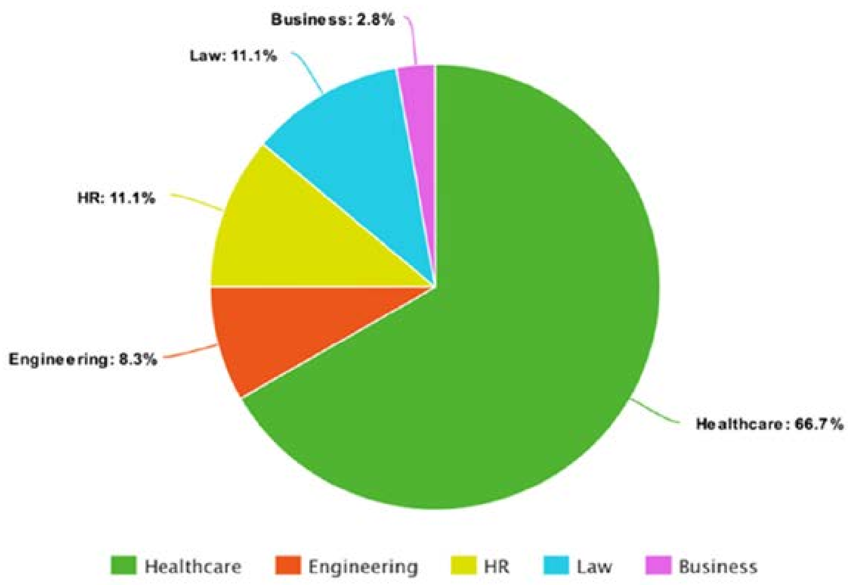

Fig. 2: Percentage of papers using NLP for DSS by domain.

3. METHOD

This paper introduces a two-stage design aimed at enhancing disaster resilience open-ended interviews. Initially, open-ended interviews were conducted with selected participants using a limited knowledge base. Each participant was provided with two open-ended questions along with their respective answers. The participants were then asked to generate follow-up questions based on the provided knowledge base. This stage aimed to assess the current level of discrepancy in existing open-ended interviews. The second stage presents our designed framework, an assistant tool, aimed at enhancing the open-ended interview process. This framework incorporates a modifiable and decent-sized knowledge base. Additionally, we propose the utilization of an NLP technique to facilitate the decision-making process by offering suggestions to the interviewer.

Ideally, a follow-up question should align with both the knowledge base and the interviewee's response, unaffected by any other factors. In this scenario, the interviewer's role is that of a mediator between the knowledge base and the interviewee. Nonetheless, as highlighted by (Gluyas & Morrison, 2014) "human beings are error prone, and the flaws are inherent in human cognitive processes, which are exacerbated by situations in which the individual making the error is distracted, stressed or overloaded, or does not have sufficient knowledge to undertake an action correctly". In this paper, this cognitive error is referred to as Interviewer's Perception. In Fig. 3, which is our perception of Jameel's design for an open-ended interview (Jameel, Shaheen, & Majid, 2018), the interviewer's perception can be seen as the extra factor highlighted in red which should either be eliminated or reduced to certain degree for data collection to be more reliable.

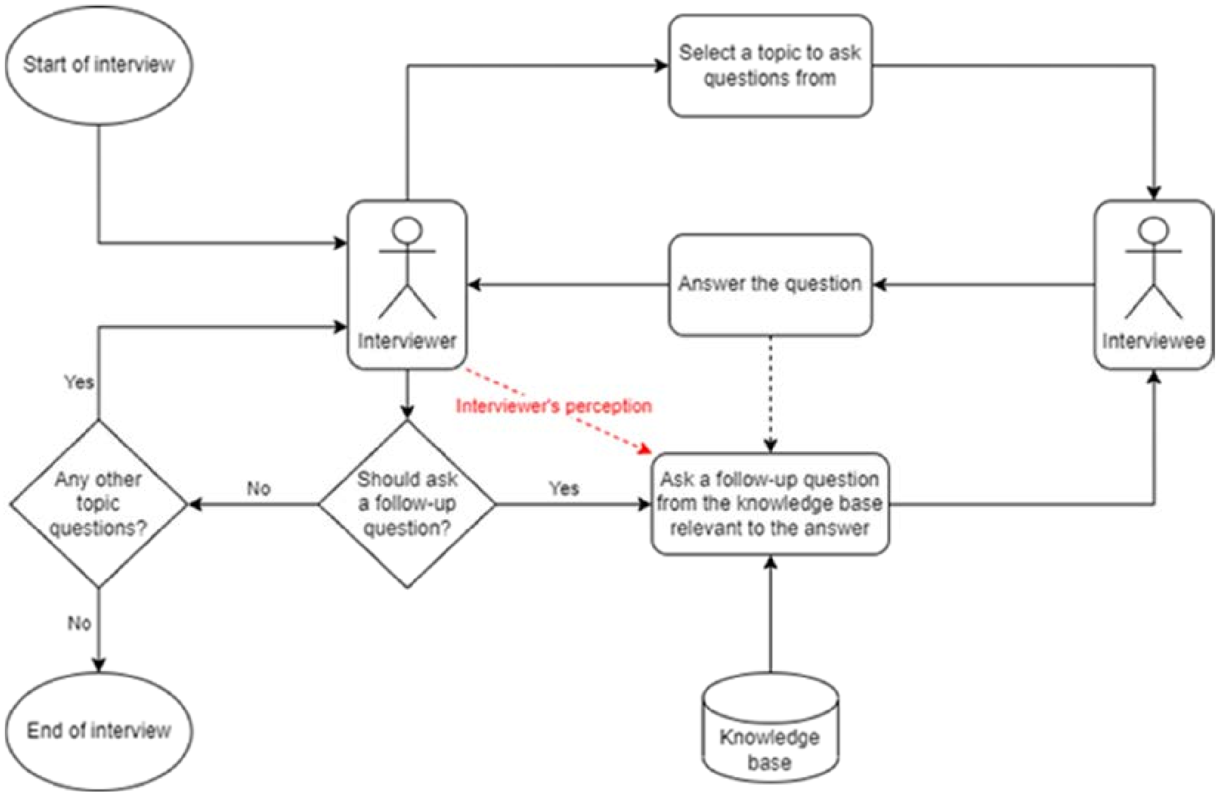

Fig. 3: Process of an open-ended interview based on our perception from Jameel's work (Jameel, Shaheen, & Majid, 2018)

An interview was strategically designed to assess the impact of interviewer's perception on the process of asking follow-up questions during open-ended interviews in the domain of disaster resilience measurement. The interview protocol comprised the following steps:

- Participants: Thirteen students with civil engineering academic backgrounds were recruited for the study. Population sample size was determined based on the number of papers published in 2022 with the keyword "open AND ended AND disaster* AND resilient*" in Scopus, which yielded thirteen papers. The Cochran's formula for small population sizes was applied with a confidence level of 95% resulting in a sample size of 13 (Nanjundeswaraswamy & Divakar, 2021).
- Interview protocol: Two sets of open-ended questions with answers were developed to elicit rich data of decision-making in open-ended interviews of disaster resilience measurement. The interview protocol included prompting the participants to elaborate on their responses and give reasoning for their decision-making thoughts. Each student is supposed to select two topics for each set of open-ended questions.
- Knowledge base: A specific knowledge base for the research domain was created by selecting the top twelve topics of peer-reviewed papers from Scopus, aligning with the keywords used in the open-ended questions in step 2. The topics were directly extracted from the papers. The purpose of the knowledge base was to enhance the interview process by narrowing down the choices for follow-up questions and reducing the need for students to possess prior knowledge for asking such questions.

3.1 Analysis

In our structured interview design, we recognize the practical constraints of interviewers reviewing numerous options during the interview process. As a result, we restricted the number of topics to a manageable dozen for each question. Each topic is supposed to cover a chain of thoughts from the interviewee's point of view. However, acknowledging that a dozen topics present limitations, it becomes evident that such a limited number may not encompass every potential point of view expressed by interviewees during an open-ended interview. In practice, a more substantial number of topics would be necessary to encompass a broader range of existing knowledge and adequately cover an interviewee's perspectives. Conversely, with a larger knowledge base, the probability of each choice being seen and selected diminishes.

To calculate the probability, we can use the complement rule. To calculate the probability of selecting at least one topic in two chances equals to the complement of not selecting a topic in two chances. If we consider the number of topics as n, the probability of not selecting a topic in one chance is (n-1)/n, and the probability of not selecting a topic in two chances is $(n-1)/n \times (n-2)/(n-1)$. Using the complement rule, the probability of selecting at least one topic in two chances can be calculated as (Lefebvre, 2009):

$$Probability\ of\ a\ topic\ selection\ in\ two\ chances\ (PTS) = (1 - (n-1)/n \times (n-2)/(n-1)) \times 100$$

Simplifying further:

$$PTS = \left(\frac{n}{n} - \frac{n-2}{n}\right) \times 100 = \frac{200}{n} \qquad (1)$$

Considering our interview scenario with only a dozen topics, the rounded value of Probability of Topic Selection (PTS) is 16.67. Obviously, the greater the n, the lower the probability of a choice to be selected and with only two topics, each of them will have the probability of 100% to be selected. Let us now examine the selection process from the knowledge base, which is executed by the interviewer to choose a follow-up topic.

In the perfect scenario, we would assume that every student only selected a pair of topics and no other topics for the follow-up questions. However, in case of reality, which probably differs from the perfect scenario, we will consider the most selected choice added to the second most selected as the probable answer and the number of times that they were selected as PA and number of times that other choices were made as SC. Thus, we can simply calculate the ratio of discrepancy by using the following formula:

$$Discrepancy\ Ratio\ (DR) = SC/(PA + SC) \times 100 \qquad (2)$$

A lower DR indicates a closer approximation to a perfect interview with minimal errors, approaching a DR score of zero. Since we had two sets of questions, we measured them both separately and reported the result with the average of them DRs as we put an equal weight on each of the questions. The maximum value of DR can only be achieved if each topic for follow-up question topic is selected exactly once or twice. In this case, PA will be equal to 6 (3 for the most selected plus 3 for the second most selected choice) and SC will be equal to total number of votes which is 26 (13 students and each of which could select 2 topics) minus the rest of the votes which is 20. By applying the formula, the result will be 77%. 77% error is a significant value that can impact data collection; thus, measuring DR in a real-case scenario is important and furthermore it implies the significance of this study. It should be noted that the value of DR can fluctuate between 0% to 77% with the median of 39%.

In order to comprehensively assess an interview's thoroughness, consistency, and the presence of discrepancies in the selection of follow-up question topics, we have devised a novel metric. This simple metric involves the multiplication of PTS and DR, with lower values indicating a more valid and reliable interview. We term this metric 'Interview's Inconsistency Mark' and it is calculated as follows:

$$Interview's\ Inconsisteny\ (IIC) = (PTS\ \times DR)/100 \qquad (3)$$

The reason that we multiply the values is the importance of DR being zero. It means that if the two obvious topics will be selected, it doesn't matter what is the probability of each topic. Considering our designed interview, the Interview's Inconsistency (IIC) can vary between zero and 12.84 (approximately 13). An IIC value of 13 indicates an interview with highly unreliable data gathering due to inconsistencies in the interviewer's follow-up questioning.

4. FINDINGS

In this section, the obtained results from the interview described in the previous section will be reviewed. The outcome of this interview provides insights into the practical aspects of conducting open-ended disaster resilience measurements by various interviewers. The interview, which simulates a real-case scenario of open-ended disaster resilience measurement, can demonstrate how significant inconsistencies can be in real-world, further implying the need of our designed decision support system. Furthermore, an exemplified DR value will be presented to facilitate a comprehensive understanding and performance comparison of our devised framework. Additionally, our framework will be introduced, aimed at assisting interviewers in formulating more consistent follow-up questions during open-ended disaster resilience interviews.

Prior to delving into the interview results and our framework, an essential concept gleaned from the literature review emphasizes the significance of a robust knowledge base during interview processes. In qualitative and open-ended interviews, interviewers are more adept at formulating relevant questions when equipped with pertinent information and prior knowledge of the subject (Kallio, Pietilä, Johnson, & Kangasniemi, 2016). As the interviewee sees the interviewer as educated and well-prepared, it aids in building trust and rapport. A strong knowledge base also enables the interviewer to go into complex subjects in more depth, pose probing questions, and elicit perceptive responses. This in turn aids in the collection of reliable data during interviews. Therefore, it is essential for interviewers to have access to a broad knowledge base which for instance, it is made from literature reviews, professional consultations, and in-depth studies to conduct effective and relevant interviews.

In addition to a solid knowledge base, interviewers must exercise caution when posing follow-up questions to avoid making arbitrary assumptions. Follow-up questions serve the purpose of elucidating or further examining specific aspects of the interviewee's response. However, by phrasing their follow-up questions based on their own beliefs or preconceived notions, interviewers unwittingly introduce bias or influence the interviewee's answers (Hunt, 2009). The objectivity and dependability of the interview data may suffer as a result. Interviewers should approach follow-up questions with an open and impartial mindset, allowing the interviewee's perspective to guide the dialogue and mitigate potential bias. Interviewers can foster a more accurate and thorough grasp of the interviewee's experiences and opinions by actively listening, refraining from asking leading questions, and keeping conscious of personal biases. Referring to Wreathall, the skill of avoiding cognitive human errors in such decision making can be achieved by investing a lot of time and effort and they need constant investment (Wreathall & Reason, 1992).

4.1 Findings from the conducted interview

In our designed interview, the first question, the first question yielded 11 and 7 selections for the most and second-most preferred choices, respectively. This implies a Disaster Resilience (DR) value of 30.77, and with the pre-calculated PTS value of 16.67, the Interview's Inconsistency (IIC) equals 5.13, indicating a moderate level of discrepancy within the range of 0 to 13. On the other hand, in our second designed interview, we obtained 12 and 9 selections for the most and second most selected choices. Upon applying the formulas, we derived an IIC of 1.35 representing a favorable level of data reliability and reduced inconsistency within the range of 0 to 13. These results indicate values falling within the lower half of the normal distribution (between 0 and 13) concerning real-world open-ended disaster resilience measurement interviews. However, this does not negate the possibility of encountering discrepancies near values such as 5.13, which align with the median value of 6.5. While these numbers serve as indicators, they emphasize the need for caution regarding inconsistency, which can potentially undermine the validity of the collected data.

4.2 Our proposed framework

To address this concern, our designed framework incorporates two essential steps. First, a knowledge base which has enough knowledge related to disaster resilience for the moment that an interviewee gives an answer to a question and the interviewer needs to ask a follow-up question from it. Second, a decision-making technique for a follow-up question selection from the designed knowledge base.

Historically, an interviewer's prior knowledge has been primarily regarded as the knowledge base. This has been one of the roots causes where we detected the inconsistency of open-ended interviews in disaster resilience measurement exists. Therefore, our primary objective in designing the framework was to establish a comprehensive knowledge base. We have identified two primary avenues for obtaining information: the existing literature on disaster resilience measurement and the expertise of disaster resilience measurement specialists. Given the considerable effort required to access and elicit knowledge from diverse experts, we deemed the first option more feasible. We opted for Scopus as our literature database, utilizing automation to extract all relevant peer-reviewed papers based on specific keywords pertaining to open-ended questions in the field of disaster resilience measurement. This automation allows us to expand beyond a limited number of topics to access thousands of thoroughly researched papers, ensuring a reliable and extensive knowledge base. During our preliminary tests of the automation system, we successfully retrieved a maximum of 1500 peer-reviewed papers for each set of question keywords that were given to the students in our conducted interview. To run queries against the knowledge base, we indexed the knowledge base with Anserini's Information Retrieval library for Python, called Pyserini, that has a low latency for information retrieval (P. Yang, Fang, & Lin, 2017). As a result, the PTS value from formula 3.1.1 equates to 0.13, implying an extremely low probability of a topic being selected from a knowledge base of this magnitude, assuming equal weightage for each topic. Conversely, this approach instils a higher confidence level in our knowledge base, encompassing a diverse range of topics that interviewers can choose from, aligning more closely with the interviewee's perspective.

In the context of decision-making techniques and drawing from relevant papers in the literature review section, we propose a methodological approach that utilizes Sentence Embedding techniques to generate follow-up questions aligned closely with the interviewee's perspective. Sentence Embedding is an NLP problem that deals with identifying text that have similarities based on context, meaning and subject etc. based on which classification, generation, syntactic parsing etc. of the text can be done (Ryu, Kim, Choi, Yu, & Lee, 2017).Given this definition, it becomes evident why this technique captured our interest. Combined as one of the most recent advancements in the field of NLP, it considers a sentence as a whole and find similarities, which in our case, sentence embedding plays the role of an interpreter in finding similar topics from a knowledge base of relevant topics in the domain of disaster resilience. To query the indexed knowledge base, we used T5 doc2query since it has the primary advantage of low retrieval latency, keeping an open-ended interview's follow up question generation to be in real-time (Nogueira, Yang, Lin, & Cho, 2019). We utilized cosine similarity to measure semantic similarity between the embeddings. The top one percent of highest-ranking topics were made available for the interviewer's selection. With these considerations, assuming a population of fifteen interviewers using our decision support system, and the algorithm identifying 1500 topics for a follow-up question, with a selection of two topics from the top one percent (15 topics), the resulting DR value could range from zero to 86.67. Although we analyzed 1500 topics, we did not observe significant progress in terms of DR. Nonetheless, it is essential to acknowledge that the user can modify the one percent value, and 1500 topics represented one of the highest feasible retrieved numbers from Scopus. Nevertheless, the IIC value from formula 3.1.3 in this context will vary between zero and 0.11, which stands in stark contrast to the actual interview with an IIC of 5.13, and even the lowest recorded case with an IIC value of 1.35, as well as the worst-case scenario with an IIC value of 13. The minimal fluctuation achieved represents a significant level of consistency for future open-ended interviews in the domain of disaster resilience measurement.

4.3 Conclusion, future works and limitations

In this article, we demonstrated the significance of consistency of open-ended interviews in the domain of disaster resilience measurement. Furthermore, with a methodological approach, we aimed to address the potential limitations of open-ended interviews by utilizing sentence embedding techniques and introducing a knowledge base to generate contextually relevant follow-up questions. By leveraging sentence embedding techniques and a knowledge base generated from peer-reviewed papers, our approach enables interviewers to gather more comprehensive and contextually relevant data during open-ended interviews. This enhanced data collection process leads to a deeper understanding of participants' experiences and viewpoints, facilitating better-informed decision-making for disaster resilience measures in construction projects.

Moving forward, potential avenues for future research and development include expanding the knowledge base by involving experts to review and contribute their insights. Additionally, continuous advancements in Natural Language Processing (NLP) algorithms offer opportunities to improve the performance and efficiency of the sentence embedding technique used in our system. Further research can explore the integration of additional data sources and domains to enhance the decision support system's versatility and applicability in diverse construction technology contexts.

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ENGINEERING ANALYSIS IMPACT ON CARBON EMISSION REDUCTION OF AN INFRASTRUCTURE PROJECT: A CASE STUDY OF SEMANTOK DAM PROJECT

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ABSTRACT: *Semantok Dam located in Semantok River Stream, Nganjuk District, East Java. Dominated by lowlands and mountains, the 1900-hectare fertile agricultural land will be irrigated by this nominated "The Longest Dam in Southeast Asia". The construction of this three kilometers long dam requires enormous resources of rockfills as the dominant material to build the main dam body. While the process of excavation, mobilization, and material settings are the dominant contributor aspects of the project's carbon footprint, at the same time this project encounter a challenge on insufficiency of existing quarry. This situation drives a comprehensive strategy not only to find the most efficient and accessible material, but also to minimize and mitigate environmental damage, ultimately by reducing the material carbon footprint. Thus, an innovative engineering solution is applied to overcome this challenge such as utilizing the available material in surrounding project site which is random rock soil by using geotechnical analysis tools for design optimization and material usage simulation also collaborating with Building Information Modeling (BIM) to visualize and calculate the estimated cost. Eventually, this analysis plays a big role in ensuring the environmental sustainability in an infrastructure project by deciding the appropriate alternative which produce the least carbon emission.*

KEYWORDS: *BIM, Carbon Footprint, Engineering Analysis, Resource Management, Sustainability*

1. INTRODUCTION

Embodied carbon represents the million tons of carbon emissions released during the lifecycle of infrastructure building materials; including extraction, manufacturing, transport, construction, and disposal. Concrete, steel, and insulation are all examples of materials that contribute to embodied carbon emissions [1]. Furthermore, other activities like excavating and earthmoving materials like rocks, soil, sand, and other similar substances can also significantly contribute to embodied carbon emissions especially when used in large volumes. The buildings and construction sector accounted for 36% of final energy use and 39% of energy and process-related carbon dioxide (CO_2) emissions in 2018 [2]. Global buildings and construction sector emissions increased 2% from 2017 to 2018, to reach a record high, while final energy demand rose 1% from 2017 and 7% from 2010. Increases were driven by strong floor area and population expansions [2].

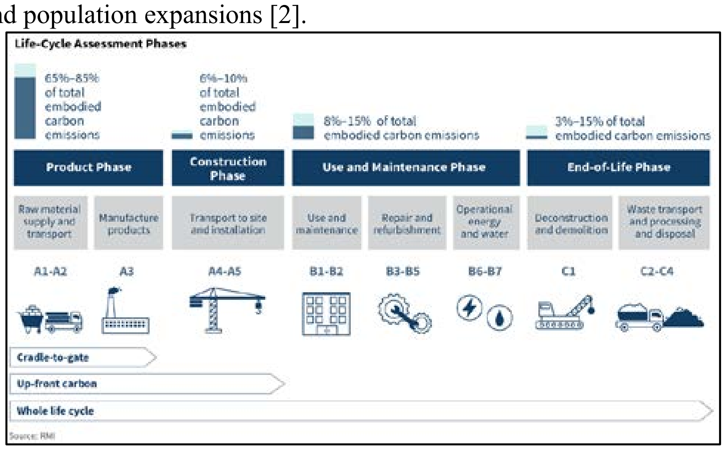

Fig. 1: Life-Cycle Assessment Phases of Embodied Carbon Emission in General Building
Source: RMI

While infrastructure buildings sector efficiency improvements continued to be made, they were not adequate to outpace demand growth. 2020 is a key year for countries to enhance their Nationally Determined Contributions (NDCs), especially concerning further actions to address energy use and emissions including embodied emissions in the buildings and construction sector [2]. Countries are innovating and implementing measures to improve efficiency and reduce emissions from their building stock. As sharing effective measures globally would amplify

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)

Gregorius A. Sentosa, Agung Fajarwanto, Amy R. Widyastuti, Achmad Luthfi Naufal, Ni Putu Pande Dhea, Abdul Rahman Kadir, Muhammad Yunus Amar, *Engineering Analysis Impact on Carbon Emission Reduction of an Infrastructure Project: A Case Study of Semantok Dam Project,* pp. 1010-1020, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.101

their impact, regional roadmaps are being developed for this purpose [2].

Indonesia seriously and consistently continues to conduct its commitment to address climate change through Low Carbon Development Planning (PPRK) [3]. PPRK is a strategic transformation of the National Action Plan for Reducing Greenhouse Gas Emissions (RAN-GRK) program as stipulated in Presidential Regulation No.61 Year 2011 [3]. As a form of consistency in efforts to address climate change, the issue is one of the national priorities that becomes a cross-cutting program in the 2015-2019 National Medium-Term Development Plan (RPJMN) document. President Joko Widodo has delivered a commitment at the UN Climate Change Conference (COP21) in Paris, France, on 12 December 2015, which is to reduce emissions by 29% (Fair scenario / using own capabilities) and by 41% (ambitious scenario / if you get international support) [3]. The commitment was ratified through Law No.16/2016 on the Ratification of the Paris Agreement to the United Nations Framework Convention on Climate Change [3]. Aligning with these commitments, Indonesia's efforts directly support the objectives of the United Nations Sustainable Development Goals (SDGs), specifically SDG 13, which is "Climate Action." By focusing on Low Carbon Development Planning and reducing greenhouse gas emissions. By synchronizing its national strategies with global sustainability targets, Indonesia not only demonstrates its dedication to combatting climate change domestically but also champions a collective global responsibility.

Carbon emissions mitigation in the construction sector is not easy. The adoption of digital construction technologies emerges as a potent strategy to mitigate carbon emissions in the construction sector. Leveraging digitalization allows architects, engineers, and stakeholders to collaboratively refine building designs, emphasizing energy efficiency. Energy efficiency could be achieved through several things, such as insulation, natural lighting, and heating and cooling systems, effectively diminishing a building's carbon output over its entire lifecycle. Digital engineering improvements such as reducing waste and promoting the selection of materials through good planning can reduce carbon footprints. Hence, embracing digitalization not only signifies technological progression but also propels industry towards the broader objective of environmentally sustainable construction and reduced carbon emissions.

2. BACKGROUND OF STUDY

The construction industry is faced with challenges such as project delays, over budget costs, quality issues, and environmental concerns. Digital construction technologies such as engineering analysis, digital survey tools, Building Information Modelling (BIM), and Geographic Information System (GIS) are proposed as a solution to these problems. The integration of those technologies plays a big role in optimizing productivity in project construction and to ensure engineering validation accuracy. The data which was given by the planning consultant will be validated so it can be executed on the field. Initial mapping is processed using digital survey tools. The mapping results are used as a basis for the BIM reality model to aid the design team gain a better understanding of the project's characteristics. Furthermore, the use of BIM enables real-time monitoring and simulating through the entire building life cycle process. GIS is utilized to enhance decision-making for continued management monitoring, reducing all risks that could arise throughout the project execution phases.

According to the Indonesian Public Works and Housing Ministry's Regulation No. 9 of 2021 on sustainable development guidelines, the implementation of BIM is mandatory. BIM facilitates the visualization of plans and their execution, ensuring a consistent interpretation amongst all stakeholders, thereby minimizing the potential for errors or misunderstandings. Although the design process is usually established at the beginning there are often real project conditions that do not match the initial design, which triggers design changes. BIM plays a crucial role in speeding up the analysis of these design alterations. With the acceleration of this decision-making process, BIM also contributes to cost and time efficiency.

Besides all the benefits that can be provided by BIM tools, to boost the impact on calculating carbon emissions on a construction project, the data produced by BIM should be integrated with comprehensive analytical calculations to ensure the carbon footprint is determined in a scientifically accurate way.

Completely eliminating carbon emissions in a project may not be an option, but the project management can control and minimize these emissions through responsible selection of materials, designs and working methods. Before making these choices, it is important to assess the impact of each option. Thus, the most effective options can be selected and implemented in the field.

This study aims to compare the embodied carbon contained in the initial design of an infrastructure project and the alternate design after validating the latest situation on the project site. The necessity for this comparison arises from differences in the field conditions, particularly the availability of materials, which did not align with the conditions assumed in the initial design.

3. PROJECT OVERVIEW

The Semantok Dam Project is one of the National Strategic Projects in Indonesia, located in the Semantok River Stream, Nganjuk District, 115 km West of the Surabaya City, East Java. The Semantok Dam's primary objectives are to lessen flood discharge and assure water availability on its coverage area during both the rainy and dry seasons due to the intense annual rainfall. The terrain of the Nganjuk district is dominated by the lowlands and the mountains, making the soil condition fertile for cultivating plants. Semantok Dam will irrigate the 1900-hectare coverage agricultural area in Nganjuk District where its existence expected to boost agricultural productivity from 186.33% to 300%. Moreover, the presence of this dam will be the new tourism destination in East Java Province.

The construction cost of this project reaches 87.9 million USD covering dewatering process, main dam, spillway, intake channel, facility building, geotechnical and hydromechanical works. With the total main dam's length of 3.1 km and height of 31.56 m, Semantok Dam is claimed as "The Longest Dam in Southeast Asia". The total capacity of the main dam is approximately 33 million m^3. The length of Semantok's spillway is 62.69 m with overflow discharge of 574.54 m^3/second. While the length of the dam's intake is 16.38 m with the tower dimension of 1.75 x 1.75 m using reinforced concrete.

According to the initial design, rockfills were used as the primary material for the dam. However, the rockfills quantity was insufficient in the existing quarry. Therefore, two alternatives were solving the problems. Firstly, choosing a new quarry where rockfills are available, but it would drive a significant cost addition and wellness issue for the surrounding society. Secondly, using the available materials in the existing quarry, which was random soil. Considering the environmental matters, Hutama Karya, as the lead contractor, validated the cost, time, and environmental implications and preferred to use random soil as the primary materials. However, a slope redesign was required, as the strength of random soil was below that of the rockfills.

4. JUSTIFICATION DESIGN

Before the construction of the dam began, Hutama Karya as the lead contractor initiated an advanced design study to ensure the feasibility of the initial design, which would then be adapted based on current field conditions. This study included a preliminary geological investigation of the construction site and a review of the dam body's zoning design, adjusted for the availability of fill materials. The consultant engineers initially developed a grouting system as the foundation for the main part of dam, however, Hutama Karya discovered the brittle and loose sandy soil layer would cause persistent water leaks over the maximum amount permitted. Hutama Karyaneeded to undertake soil analysis to determine alternative design methods and ensure the dam would be strong enough to contain water from intense rains without flooding. The results from the initial geological investigation of the construction location differed from the initial planning design, necessitating further studies into the dam foundation repair plan.

The Bendoasri and Teritik Quarry are still on the planning stage. In the initial design provided by the consultant engineers, the zoning of the dam body is an upright core type with rockfill. However, based on the results of the initial geological investigation on construction phase, the two quarries did not have sufficient stone material available. The quantity/volume of stone material availability was quite limited, on contrary random soil material was abundant. The plan became difficult to accomplish, as the nearby quarry could not produce enough rock for the long dam without deep damaging excavation. Another option is digging a new quarry for the site, but that would be costly.

The insufficiency of rockfills in the existing quarry is one of the biggest matters in the Semantok Dam Project. Due to environmental and material availability considerations, the project team replaced the rockfills with random soils – available material in the fields. However, the random soil strength was below the rockfills. The insufficiency of rock created risk to potentially redesigning the dam slope. Engineering analysis software was utilized to model the material replacement and verify whether the initial slope design was still applicable in the fields.

In the beginning, Hutama Karya tried to model the random soil in the initial design and found that the safety factor of the slope (1.183) was below the minimum requirements (1.302) and showing that the slope was inapplicable. Thus, with engineering analysis software, a process of trial and error was undertaken to find the safest and most optimized design. As a result, the assessment indicated that the slope should have a steeper incline of 1:3 on the left side and 1:2.75 on the right side to produce the safety factor of 1.644, which fulfilled the minimum requirements. Not only did solve the problems, but also able to gain more value in terms of materials and method efficiently. Hutama Karya was able to avoid 1.8 million USD of reworking by renewing the slope design.

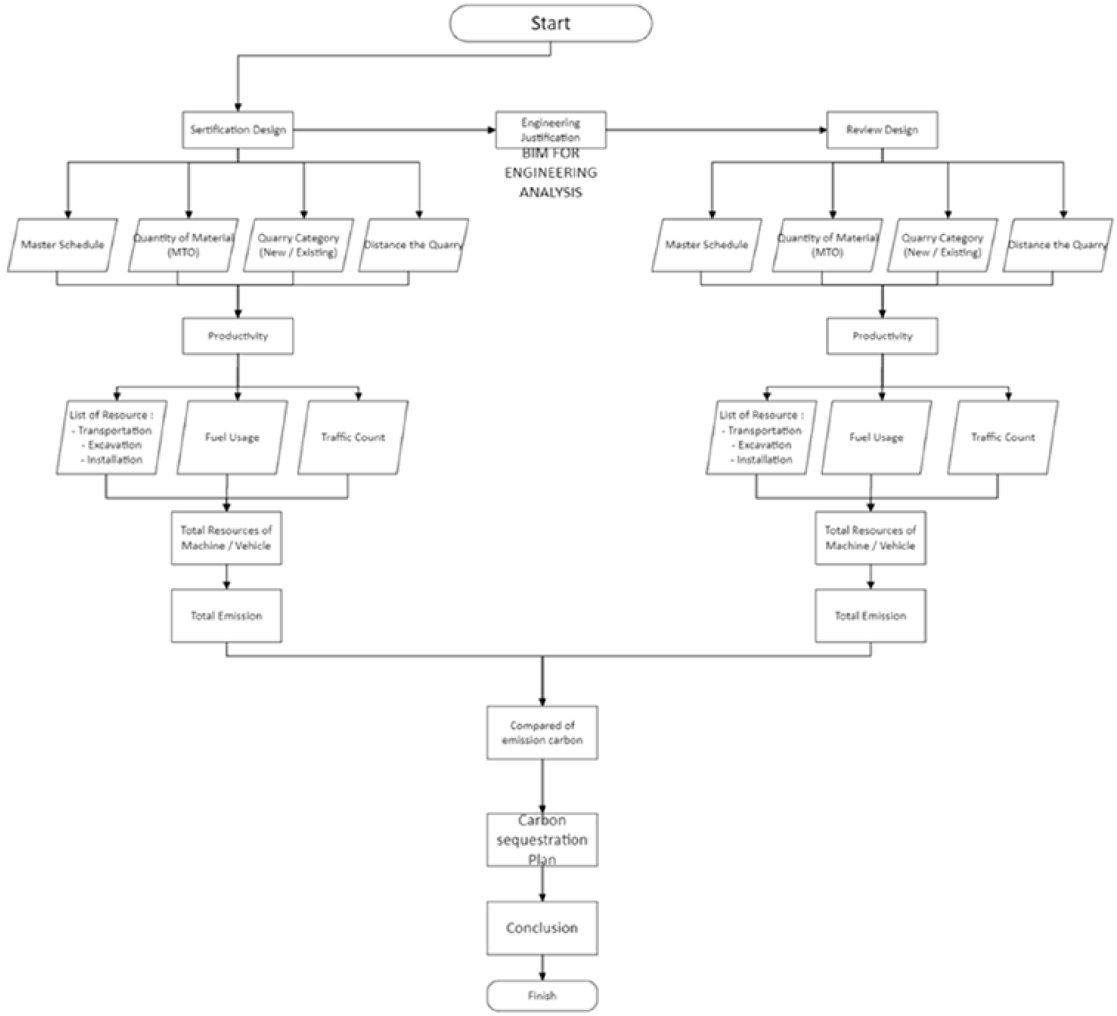

Fig. 2: Calculation Flow

5. LIMITATION OF STUDY

This study will focus on emphasizing the calculation of the carbon footprint arising from design changes because of engineering justification using Building Information Modelling (BIM) & engineering analysis software. In this context, the case that becomes the focus point is the change in the selection of the main material used in the construction of the dam body.

This process of calculating the carbon footprint does not cover all aspects of construction, but rather focuses on some essential elements that are directly affected by changes in design. These aspects include the creation of a new quarry which is the main source of construction materials, the distance of material delivery from the quarry to the construction site, the number and type of equipment used in material delivery and the construction process itself.

Therefore, this study aims to provide a clear and comprehensive picture of how design changes using BIM and engineering analysis software can affect the carbon footprint in construction projects and provide a foundation for more informed and sustainable decision-making.

6. CALCULATION METHODS

This Figure shows the flow of study methods.

In this study, as illustrated in Figure 2, the calculation method involves comparing two distinct scenarios. In the first scenario, we consider the initial design or Design Certification, which upon implementation, has been found lacking in terms of material sufficiency. The available quarry is incapable of providing the necessary quantity of materials, leading to the need for another quarry that is considerably distant from the project site.

The second scenario maintains the usage of the first quarry that planned available material, in proximity to the project site but demands alterations in the design, necessitating recalculations and technical justifications. The changes are to ensure that the local materials meet the specifications required for dam construction. But the first quarry was originally a pine forest area, so the utilization of the quarry will require land conversion, also calculate how much carbon stock is lost and how many trees were cut down to facilitate reforestation after construction finished.

Data is collected for both scenarios, including the quantity of materials needed per the initial and revised designs, the dam project completion schedule, and the distance between the quarry and the project site. From these data, we can establish productivity targets for the work, thus enabling the detection of resource requirements.

After determining the necessary equipment, the next step is to calculate fuel consumption during the construction process for each heavy equipment used. Once the total fuel used is determined, this amount is then converted to a form of energy. Energy conversion from the use of diesel fuel to other forms of energy is an average of 38.243 MJ/Liter or 38.243 x 10^-6 TJ/Liter. After being converted to a form of energy (TJ), the next step is to calculate the resulting carbon emissions. To calculate this, we use a formula derived from the IPCC Guidelines for National Greenhouse Gas Inventories (2006).

$$Emission = \sum_{j}^{n} \left(Fuel_j \times EF_j\right) \quad \text{(1)}$$

Where:

Emission = Total of Emission (Kg)

Fuel = Fuel Consumed (TJ)

EF = Emission Factor (Kg/TJ)

j = Fuel Type

For the type of fuel, all heavy equipment used uses diesel oil. The emission factor for the type of diesel oil fuel is 74,100 Kg/TJ, as shown in Table 1.

Table 1: Road Transport Default CO_2 Emissions Factors and Uncertainty Ranges

Fuel Type	Default (Kg/TJ)	Lower	Upper
Motor Gasoline	69300	67500	73000
Gas / Diesel Oil	**74100**	**72600**	**74800**
Liquefied Petroleum Gases	63100	61600	65600
Kerosene	71900	70800	73700
Lubricants	73300	71900	75200
Compressed Natural Gas	56100	54300	58300
Liquefied Natural Gases	56100	54300	58300

Source: IPCC Guidelines for National Greenhouse Gas Inventories (2006)

Subsequently, these results are utilized to calculate the carbon emission resulting from each scenario. Finally, the data from both scenarios is compared to draw insightful conclusions then plan to replace the carbon lost due to land conversion.

7. DATA COLLECTION

As initial information, to find out the body parts of the dam, below is a typical picture of the cross section of the dam building structure.

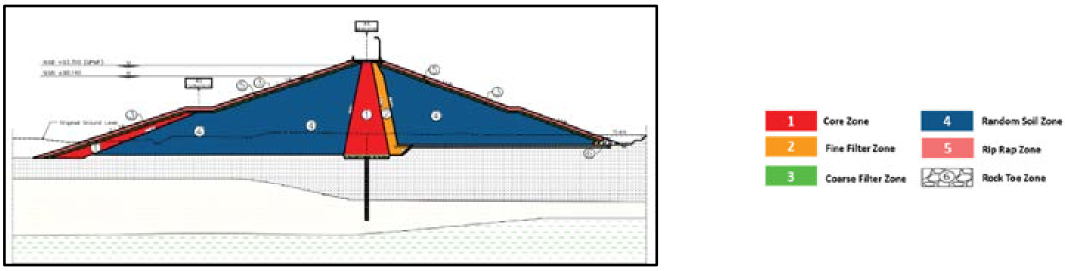

Fig. 3: Typical Cross Section of Dam

The insufficient material is in the Zone 4, which is the most dominant part of the entire dam structure, comprising 67% of the total volume of the dam. According to the master schedule and contract, the work on the zone four must be completed within 24 months or 730 Days to avoid disrupting subsequent tasks. The quarry has two alternative locations. The first quarry is in the Bendo Asri & Tritik area, but it does not contain rock soil materials that passed the required specifications. The second quarry is in the Blitar & Kediri area and the rock soil materials there passed the required specifications. Figure 4 shows the distance between the project's site to each quarry. The distance to the first quarry is approximately 10.5 Km and the distance to the second quarry is approximately 84.6 Km.

Fig. 4: Distance Between First Quarry (Bendoasri & Tritik) and Second Quarry (Kediri & Blitar) with The Project

The result of the assessment on the potential quarry sites shows that the first quarry is in an area originally covered by a pine forest. Utilizing this site would convert the landscape of the surrounding area from forest to quarry. The second quarry, for comparison, is a pre-existing site so there is no additional land conversion would be required for it to be operational, but it has downside which is the distance between the quarry and the project's site.

7.1. Initial design / design certification

This project's initial design stage is also known as the design certification. At this stage, the initial design specifies Rockfills material for the zone four of dam's body. The material shall be obtained from quarry sources in the Bendoasri and Tritik localities, approximately ten kilometers from the project site, as shown in Figure 4. Based on Table 2, the initial design data indicates that rockfill material can be sourced from the Bendo Asri & Tritik quarry, ensuring sufficient supply.

Table 2: Initial Condition Based on Design Certification

Material	Before Soil Investigation					
	Volume required (m^3)	Volume Quarry (m^3)	Location	Distance (KM)	Ratio	Availability
Rockfills	1,998,934	2,390,000	Bendo Asri &Tritik	10	1.20	Fulfilled

Upon further soil investigation in the pre-construction phase, it was found that the quarry did not contain rockfill material that met the initial design specifications, rendering it unsuitable as a rockfill quarry. To address this issue, an alternative location was sought that contained rockfill material meeting the specifications. A suitable quarry was found in the second quarry at the Kediri and Blitar areas, approximately 85 KM away, as illustrated in Figure 4. Therefore, Case A involves replacing the original quarry with the second quarry, which contains suitable rockfill material. This switch leads to changes in the data, as depicted in Table 3.

Table 3: Initial Condition Based on Design Certification After Change to Second Quarry

Material	Alternative Quarry After Soil Investigation					
	Volume required (m^3)	Volume Quarry (m^3)	Location	Distance (KM)	Ratio	Availability
Rockfills	1,998,934	3,107,000	Kediri & Blitar	85	1.55	Fulfilled

7.2. Design change / design review

Following the soil investigation, it was discovered that most of the material at the original quarry located in Bendo Asri & Tritik, is random soil. To prevent relocating the quarry, a design review was conducted, which involved changing the dam body material from rockfills to random soil. Hutama karya determined that the design issues can be solve by using reality modeling and geotechnical design.

First, a laser scanner undertook at the project area, created point clouds, and molded them into a digital replica of the site by using Context Capture Software. The digital replica helped the project team understand the existing condition of the field and plan local quarry locations, minimizing the excavation depth to limit the impact on the environment. The team then imported reality modeling data into their bespoke project management information system, giving the project manager insight into real-time conditions. Next, the organization then augmented the reality model with geotechnical analysis via Plaxis Software, enabling them to simulate foundation options and test the groundwater flow. Plaxis enabled them to model soil fill within the proposed dam design and test its performance within the area's terrain. Though the initial slope design did not meet safety requirements, they used OpenRoads Designer Software to evaluate other slope designs, eventually realizing that a greater slope on the left side of 1:3 combined with a lesser slope of 1:2.75 on the right side would meet safety requirements for both construction and operations while incorporating the sandy soil as fill. This adjustment will increase the safety factor and strength, leading to an expansion in the volume of the dam body in Zone 4. Accordingly, fortification calculations were conducted using the Plaxis and OpenRoads Designer Software, as shown in Figure 5.

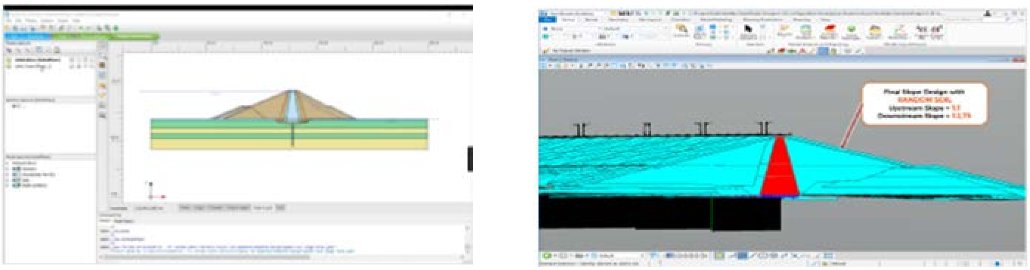

Fig. 5: Redesign Calculation of the Dam Body Using Plaxis and OpenRoads Designer Software

Lastly, to ensure the changes to the design would not impact the tight deadline, Hutama Karya simulated the construction with Synchro Software. In addition to testing the construction feasibility of the new design, the application helped them plan the construction process.

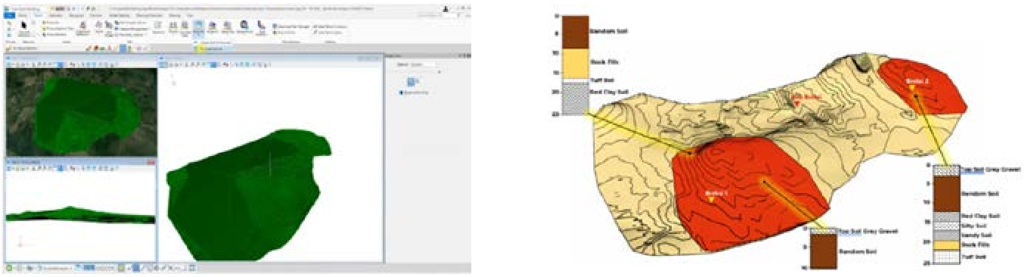

Fig. 6: Quarry BendoAsri & Tritik Classification & Quantification Using OpenRoad Designer

As shown in Figure 6, to ensure the availability of the quarry in that area, the quarry volume was recalculated using BIM to speed up the quantification process. Material take off generated from a 3d model created in OpenRoad Designer Software to help the engineers accurately visualize upon calculation, it was estimated that there is 5.3 million cubic meters of random soil available. Therefore, the first quarry is still utilized, but changes are made to the dam body design so that random soil material can still be used, as indicated in Table 4.

Table 4: Condition After Design Review Using the Random Soil Material at First Quarry

Material	Random Soil in First Quarry after Design Review					
	Volume required (m^3)	Volume Quarry (m^3)	Location	Distance (KM)	Ratio	Availability
Random Soil	2,308,176	5,326,000	Bendo Asri &Tritik	10	2.31	Fulfilled

The first quarry is currently a pine forest owned by Perhutani. When this pine forest is converted into a quarry location, the carbon stock will disappear. Therefore, to comply with existing regulations and to support sustainable project achievement towards the SDGs, Hutama Karya, as the contractor, is obliged to replace the carbon at the quarry site by reforesting after the project is completed and the quarry is no longer in use.

Table 5: calculation of the amount of carbon lost from land conversion.

Area Quarry (m^2)	Area Quarry (Ha)	Type of Tree	Amount of Tree	Carbon of each tree ($KgCo_2$/Pine)	Total Amount of Carbon ($KgCO_2$)	Total Amount of Carbon ($TonCO_2$)
200,000	20	Mercus Pine	141,541	22.60	3,198,827	3,199

According to the data in Table 5, it turns out that by converting a 20-hectare pine forest, a carbon reserve of 3,200 tons of CO_2 will be lost. This loss will be offset by reforestation after the project is completed.

8. DATA PROCESSING

The data calculation begins with the collection of initial data, followed by determining the productivity targets for each case based on the distance and travel time to the quarry, as well as the execution time (work schedule and working hours). The results of these calculations can be seen in Table 6.

Table 6: Comparison Resume of Initial Data & Target Productivity each Case

No	LIST	CASE A		CASE B	
1	Materials	Rockfills		Random Soil	
2	Volume required (m^3)	1,998,934	m^3	2,308,176	m^3
3	Volume Quarry (m^3)	3,107,000	m^3	5,326,000	m^3
4	Location Quarry	Kediri & Blitar		Bendo Asri &Tritik	
5	Ratio Stock Quarry	1.55		2.31	
6	Availability	Fulfilled		Fulfilled	
7	Quarry Type	Existing Quarry		New Quarry	
8	Distance From Project (KM)	85	KM	11	KM
9	Duration Quarry - Project (Minute)	160	Minute	25	Minute
10	Work Hour in a Day	8	Hour	8	Hour
11	Schedule Duration of Work	730	Days	730	Days
12	Target Productivity/day	2,738	m^3/day	3,162	m^3/day

After determining the productivity targets, the next step is to ascertain the equipment needs for each case. To simplify this process, equipment needs are determined for three different locations: the equipment located at the quarry site, the equipment used for construction processes, and the equipment needed for transportation processes.

As seen in Tables 7, 8, and 9, these illustrate the heavy equipment requirements for Case A, calculated based on the work's productivity targets, along with an estimate of fuel consumption for each location.

Table 7: Equipment Requirements & Fuel Consumption at the Quarry Location (Case A)

Equipment	Type	Unit	Fuel Type	Consumption/ Hour/ Machine	Work Hour	Project Duration (Days)	Fuel Consumption		Total Consumption
							(liter/h)	(Liter/ day)	
Excavator 01	Operational Weight 20T	3	Diesel	14	8	730	42	336	245,280
Excavator 02	Operational Weight 30T	1	Diesel	20	8	730	20	160	116,800
Excavator 03	Operational Weight 50T	1	Diesel	40	8	730	40	320	233,600
Excavator 04	Breaker	6	Diesel	25	8	730	150	1200	876,000
TOTAL CONSUMPTION (Liter)									1,471,680

Table 8: Equipment Requirements & Fuel Consumption at the Main Dam Location (Case A)

Equipment	Type	Unit	Fuel Type	Consumption/ Hour/Machine	Work Hour	Project Duration (Days)	Fuel Consumption		Total Consumption
							(liter/h)	(Liter/day)	
Bulldozer	D85SS	5	Diesel	22	8	730	110	880	642,400

VibroSmooth	SD 110	5	Diesel	18	8	730	90	720	525,600
VibroPadfoot	SD 110	5	Diesel	19	8	730	95	760	554,800
TOTAL CONSUMPTION (Liter)									**1,722,800**

Table 9: Equipment Requirements & Fuel Consumption of the Transportation (Case A)

Equipment	Type	Unit	Fuel Type	Travel Speed (KM/h)	Average Consumption		Mileage (Km)	Trip/ DT	Project Duration (Days)	Total Consumption
					(liter/h)	(liter/km)				
DumpTruck	Capacity 30T	72	Diesel	30	50	1.67	84.5	2.3 Times	730	17,025,060
TOTAL CONSUMPTION (Liter)										**17,025,060**

Based on the data above, the total fuel consumption for Case A is 20,219,540 liters.

Next, the calculation of heavy equipment requirements and fuel consumption on Case B, calculated based on productivity targets, can be seen in Tables 10, 11, and 12.

Table 10: Equipment Requirements & Fuel Consumption at the Quarry Location (Case B)

Equipment	Type	Unit	Fuel Type	Consumption / Hour / Machine	Work Hour	Project Duration (Days)	Fuel Consumption		Total Consumption
							(litre/h)	(Litre/ day)	
Excavator 01	Operational Weight 20T	3	Diesel	14	8	730	42	336	245,280
Excavator 02	Operational Weight 30T	1	Diesel	20	8	730	20	160	116,800
Excavator 03	Operational Weight 50T	1	Diesel	40	8	730	40	320	233,600
Excavator 04	Breaker	4	Diesel	25	8	730	100	800	584,000
TOTAL CONSUMPTION (Liter)									**1,179,680**

Table 11: Equipment Requirements & Fuel Consumption at the Main Dam Location (Case B)

Equipment	Type	Unit	Fuel Type	Consumption/ Hour/Machine	Work Hour	Project Duration (Days)	Fuel Consumption		Total Consumption
							(litre/h)	(Litre/day)	
Bulldozer	D85SS	4	Diesel	22	8	730	88	704	513,920
VibroSmooth	SD 110	4	Diesel	18	8	730	72	576	420,480
VibroPadfoot	SD 110	4	Diesel	19	8	730	76	608	443,840
TOTAL CONSUMPTION (Liter)									**1,378,240**

Table 12: Equipment Requirements & Fuel Consumption of the Transportation (Case B)

Equipment	Type	Unit	Fuel Type	Travel Speed (KM/h)	Average Consumption		Mileage (Km)	TRIP / DT	Duration Project (Days)	Total Consumption
					(litre/h)	(litre/km)				
DumpTruck	Capacity 30T	62	Diesel	30	50	1.67	10.5	6 Times	730	4,752,300
TOTAL CONSUMPTION (Liter)										**4,752,300**

Based on the data on Table 10, Table 11 and Table 12, the total fuel consumption for Case B is 7,310,220 liters.

After calculating the total equipment and fuel needs for Case A and Case B, the next step is to convert the total fuel consumption into energy (TJ). This is done by multiplying the total fuel consumption requirements by the specific heat of diesel fuel. The results of these calculations can be seen in Table 13.

Table 13: Conversion the Consumption of Fuel (Liter) to the Consumption of Energy (TJ)

Energy Conversion Calculation	CASE A		CASE B	
Consumption (Litre)	20,219,540	Litre	7,310,220	Litre
Calor Specific (TJ/Litre)	0.000038243	TJ/Litre	0.000038243	TJ/Litre
Consumption (TJ)	**773.255868220**	**TJ**	**279.564743460**	**TJ**

Once all the necessary data is available, the next step is to calculate the carbon emissions generated from each case using the emissions formula (1). The efficiency factor of CO_2 for diesel type is approximately 74,100 (Kg/TJ). The results of the comparison can be seen in Table 14. The table shows that in Case A, there is no additional carbon emission from land conversion, whereas in Case B, the carbon emission is increased due to the land being converted from a pine forest to a quarry. Therefore, the total emissions generated from Case A and Case B are 57,298 Ton and 23,914 Ton respectively. This results in a difference in emissions between the two cases of 33,383.69 Ton.

As a result, Hutama Karya, the main contractor, has chosen Case B, which contains lower carbon emissions than Case A. In response, Hutama Karya will also implement a carbon recovery plan by reforesting a 20-hectare area at the Bendoasri and Tritik quarry sites. This initiative is taken to support the Sustainability Development Goals

13 Climate Action.

Table 14: Emission Carbon Calculation

Emission Calculation	CASE A		CASE B	
Consumption (TJ)	773.255868220	TJ	279.564743460	TJ
EF CO_2 Diesel	74100	(kg/TJ)	74100	(kg/TJ)
Emission (Kg)	57,298,260	Kg	20,715,747	Kg
Emission (Ton)	57,298.26	Ton	20,715.75	Ton
Emission From Land Use Change				
Pine Mercussi to Quarry	-	Ton	3,198.83	Ton
Total Emission	**57,298**	**Ton**	**23,914.57**	**Ton**

9. CARBON RECOVERY PLAN & SUSTAINABLE CONSTRUCTION

Hutama Karya, in its commitment to sustainable development, plays a significant role as a contractor in the construction of the Semantok Dam. As part of their responsibilities, they have implemented reforestation initiatives in response to the conversion of the quarry land. Hutama Karya has planted over 2,000 trees on the former quarry site and an additional 6,000 trees in the surrounding dam area. Additionally, they have planted Vetiver Grass to stabilize the slopes of the spoil bank, which is made of excavation waste material. The project was completed in 2022, and Reforestation efforts continue periodically even today.

Fig. 7: Iriana Joko Widodo, The First Lady, planted date palm trees as a symbol of environmental awareness (Left Side), tree planting and fish hatchling activities by Central & Local Government (Right Side)

In figure 7 (on the left side) during the inauguration of the Semantok Dam, Iriana Joko Widodo planted date palm trees as a symbol of environmental awareness. On the right side of Figure 7, enthusiasm for reforestation also received support from both the central and local governments, who have participated in tree planting and fish hatchling releases into the dam. These efforts are part of a recovery plan intended to replace the lost carbon reserves and support SDG number 15: Life on Land, as Carbon recovery plans often involve afforestation and reforestation initiatives, which help restore land and create wildlife habitats.

The reforestation activities may not be enough to replace the lost carbon completely because this project still produced substantial amount of carbon. However, the benefits of constructing this dam are also substantial, contributing to sustainable infrastructure. When related to the SDGs, these benefits include SDG 2 (Zero Hunger): The dam enhances the planting intensity from 186% to 300%, supplies raw water at a rate of 312 liters per second, equivalent to potable water connections for 28,000 houses, thus driving rapid economic growth and increasing agricultural productivity. SDG 6 (Clean Water and Sanitation): Dams store water and are critical for providing clean water and sanitation facilities. They can also aid in waste management and help improve water quality. SDG 7 (Affordable and Clean Energy): Many dams are utilized to generate hydroelectric power, a form of renewable energy. SDG 8 (Decent Work and Economic Growth): The dam's construction creates new job opportunities, not only in agriculture but also in fish farming and the tourism sector. SDG 15 (Life on Land): The construction of a dam often involves land use changes and can significantly impact local ecosystems and biodiversity. Mitigation measures, such as creating new habitats or corridors for wildlife, can help reduce these impacts. Semantok Dam created a more sustainable infrastructure towards healthier environment, improved human well-being, and boosted economic growth.

10. CONCLUSION

The Semantok Dam Project, identified as one of the National Strategic Projects in Indonesia, is located in the Semantok River Stream in Nganjuk District. It's situated 115 km west of Surabaya City, East Java. With the dam's total length extending to 3.1 km and a height of 31.56 m, it's proudly recognized as “The Longest Dam in Southeast Asia.”

Digital construction technologies such as engineering analysis, digital survey tools, and BIM played a significant role in the project, primarily in acceleration of analysis on design modifications. This acceleration of the decision-making process has resulted in enhanced cost and time efficiency. However, despite BIM's effectiveness as a novel method, it has limitations, notably in computing the impact of carbon emissions on a construction project. This aspect is yet to be fully optimized and requires further development. As a result, a comprehensive analytical calculation is necessary to precisely determine carbon emissions.

In the initial design, rockfills served as the primary material for the dam. However, the quantity available in the existing quarry was insufficient. Consequently, there are two alternatives that emerged to address this problem. Case A proposed sourcing from a new quarry where adequate rockfills were available, but this option posed significant additional costs and potential health concerns for the local community. Case B suggested using the available materials, particularly random soil. However, this would require converting a pine forest area into a quarry, leading to significant land-use change.

Data were collected for both scenarios, including the quantity of materials required according to the initial and revised designs, the dam project's completion schedule, and the distance between the quarry and the project site. This information facilitated the establishment of productivity targets. The productivity targets would, in turn, guide the determination of resource requirements.

The total emissions generated from Case A and Case B were 57,298 tons and 23,914 tons, respectively, resulting in a difference in emissions between the two cases of 33,383.69 tons. The analysis revealed that Case B, which involved transforming a pine forest into a quarry, resulted in lower carbon emissions compared to Case A. However, this land-use change led to a loss of carbon reserves. The project contractor, Hutama Karya, addressed this issue through a carbon recovery plan involving reforestation. More than 6,000 trees were planted around the dam area and at the quarry sites, with an additional 2,000 trees planted on the former quarry land. Vetiver grass was also planted to strengthen the dam’s slopes.

These ongoing recovery efforts demonstrate alignment with SDG 15 - 'Life on Land,' illustrating a commitment to sustainable practices. The dam's construction supports not only SDG 15 but also aligns with other SDGs. These include SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), and SDG 8 (Decent Work and Economic Growth). The project has thus far demonstrated substantial benefits, including increased planting intensity, a steady supply of raw water, creation of new job opportunities, and the provision of clean, affordable energy.

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SOLAR POTENTIAL AND ENERGY ASSESSMENT DATA IN U-BEM MODELS: INTEROPERABILITY ANALYSIS BETWEEN PERFORMANCE SIMULATION TOOLS AND OPENBIM/GIS PLATFORMS

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ABSTRACT: *To evaluate the energy and solar potential of the building stock and address feasibility studies of building retrofit interventions information standards are required to ensure proper data flow from building and urban models to simulation environments. Energy performance data are gathered from different information containers and therefore the result of simulations needs to be shared in BIM/GIS environments to better address energy policies and decision-making processes. Solar potential and energy retrofit estimation, developed by means of urban models (U-BEM) are too rough to support a decision-making process, even if at a feasibility stage. On the opposite, strategic decisions are defined with reference to large building stocks that require a U-BEM approach. To increase the reliability of this kind of simulations the study proposes to integrate U-BEMS with BIM-based data that are aggregated and published at urban scale as average performance indicators of built systems. The interoperability problem is analyzed both for simulation tools that need to manage this kind of data and openBIM/GIS platforms that need to share performance indicators and simulation results.*

KEYWORDS: *Energy potential, Solar potential, IFC, BIM, U-BEM.*

1. BACKGROUND

The necessity to take action in the constructed environment, encompassing both individual structures and entire urban areas, stems from the increasing significance of enhancing comfort levels and energy efficiency. This need arises due to mounting environmental issues and the imperative to reduce energy consumption (Ratti et al., 2005). With urbanization and the increasing impact of buildings on energy demand, there is a crucial demand for accurate predictive models that can guide sustainable urban development (Amado & Poggi, 2012).

Traditionally, urban energy planning and building design analyses have been based on generic models, leading to suboptimal energy performance and inefficient resource utilization (Lan et al., 2022). Due to this reason, it becomes imperative to establish precise information standards that ensure seamless data transfer from architectural structures to urban models, encompassing both geometric and climatic data. These standardized procedures will facilitate, for example, the transmission of initial solar potential assessments within simulation environments. To overcome all the limitations, the development of sophisticated and reliable predictive models has become necessary (Lobaccaro et al., 2019). Such models can provide, in a simulation environment, valuable insights into the solar potential of different urban areas, allowing city planners, architects, and experts to make informed decisions regarding energy-efficient designs, renewable energy integration, and also climate-responsive urban planning (Kabir et al., 2018).

The examination of outcomes from the new solar potential estimation applications, reveals a noteworthy decrease in the computed potential once the feasibility of installing energy production systems like photovoltaics is assessed. Analyzing the solar potential of buildings allows for the swift identification of surfaces significantly impacted by solar irradiation, evaluating the more suitable for incorporating active solar systems. However, if this assessment is conducted on an overly simplistic model, assuming all surfaces possess a uniform level of adaptability, it fails to accurately reflect the true solar potential.

Likewise, concerning the energy retrofit of existing buildings, it is crucial to confirm the practical feasibility of upgrading building envelopes and technological systems with energy-efficient technologies. This verification should occur within a comprehensive information model aimed at identifying transformation barriers that could potentially impact feasibility studies. Such a model would help reference point challenges that might arise during the retrofitting process and ensure a more accurate assessment of the retrofitting potential.

The essence of the issue lies in the requirement for simulations to rely on a dependable information foundation, which necessitates a detailed representation of buildings. However, such detailed data is often unavailable during the preliminary stages of the study. Consequently, it becomes imperative to establish a system that enables the

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Carlo Zanchetta, Martina Giorio, Maria Grazia Donatiello, Federico Rossi, Rossana Paparella, *Solar Potential and Energy Assessment Data in U-BEM Models: Interoperability Analysis Between Performance Simulation Tools and OpenBIM/GIS Platforms,* pp. 1021-1032, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.102

enrichment of urban models with more accurate values for the subsequent calculation of the solar potential data and the energy retrofit. Such models must integrate irradiation conditions on architectural surfaces depending on their exposure and geographical location with a broader range of factors influencing energy production and transformation to ensure more precise and reliable simulations.

In fact, the building sector lacks a method that makes it possible, in a relatively short period of time, to assess the real renovation potential of an existing building and, therefore, to identify, at a preliminary level, the optimal intervention strategy. The lack of information on the transformation of the existing building, on the one hand, and the enormous potential offered by the development of new technologies, on the other, make it necessary to identify a plan for evaluating the renovation potential of buildings.

The literature analysis revealed that, to date, the only tool for formulating energy efficiency design hypotheses is the energy diagnosis. This is a rather time-consuming process, as well as an economic one. Hence, the need to formulate an expeditious methodology for assessing existing buildings. (Mazzarella & Piterà, n.d.)

Some attempts have been made to propose a method for defining a building potential in Italy, but these go beyond the concept of transformability, which is intrinsically linked to the technological element, and outline intervention scenarios that are compatible with the valuable characteristics of a historic building, such as ENEA method. In turn, the intervention is ranked according to a score determined based on effectiveness, durability, compatibility, and cost-effectiveness (Boriani et al., 2011). Other attempts to propose a methodology to analyze buildings are represented by TABULA project and CRI_TRA method. TABULA focuses on the proposal of a census of building types and their optimization by simulating the effects of possible retrofitting interventions (Corrado et al., 2014), while the CRI_TRA method is very close to what is proposed in the rest of this research activity. It is configured as a study of the criticality and transformability exhibited by the public housing sector through the assignment of a numerical score to the two indices, GDC and GDT (Diana, 2017).

2. METHODOLOGY

To achieve the delineated results, the study proposes to integrate simplified models with "transformability coefficients" that considered the adaptability and potential of various building surfaces and technical elements to harness solar energy effectively. By identifying surfaces that are most susceptible to solar irradiation, the integration of this coefficient with the simulated data offers a more precise representation of the real potential within the urban context.

To establish these coefficients, a representative selection of detailed building models was analyzed. These detailed models serve as a basis for deriving coefficients that reflect the unique characteristics of different surface types and facades. The coefficients were identified inside the entire urban area using characteristics such as the age of the buildings and the architectural similarities. Integrating the coefficients into the subsequent simulation process ensures that the data are based on more realistic and specific information.

The geographic information system (GIS) environment plays a crucial role in this methodology, enabling the integration of various data sources, such as climatic data from terrestrial or satellite weather stations, building geometries, and urban morphologies, in the calculation of the solar potential data. Through this integration, the GIS platform acquires data from 3D simulations that take into account solar irradiance, local weather conditions, and the complex interplay of sunlight with urban elements (Bahu et al., 2013).

Moreover, the simulation outcomes do not only focus on solar potential estimation for photovoltaic installations but also extend to solar thermal systems. This broader perspective enables a comprehensive evaluation of the renewable energy potential available in the urban context, encouraging the adoption of different and integrated renewable energy solutions.

By applying this methodology to the North Piovego University area in Padua, Italy, the study demonstrates its applicability to real urban scenarios. The study area selected for analysis covers approximately 50,000 m2 and it is located in northern Italy. By integrating detailed building data, geographic information, and solar simulation techniques, this approach provides a robust foundation for optimizing energy efficiency, promoting renewable energy integration, and fostering sustainable urban development.

2.1 Source data for modeling

Urban data and weather data are closely related to a geographical location and a determined time. Geospatial data can take different forms: raster, vector, and graph data. Raster data is a gridded matrix, organized in rows and columns. Vector data represent information through points, lines, and polygons. Graph data are represented by edge and node and generally take the form of road networks (Lee & Kang, 2015). Since raster data always have a standard dimension, they are considered more basic than vector data, which, on the contrary, are discrete. The union of raster and vector data makes the geographic database. The sources of these data are manifold and in recent years there has been a radical change in the way the maps are created. While maps were previously only created by national land mapping agencies, in the 2000s, thanks to the elimination of intentional GPS degradation, a new way of creating maps was born (Haklay & Weber, 2008). The accuracy of GPS, introduced in all mobile devices, gives any citizen the possibility of entering information into maps. Numerous studies have named this phenomenon differently. They speak of Volunteered Geographic Information (VGI) (Goodchild, 2007), neogeography (Rana & Joliveau, 2009) and crowdsourcing geospatial data (Heipke, 2010). The peculiarities of this phenomenon are:

- data are much more varied than in official cartographies because anyone can add information to the map;
- data are available for any part of the world even for places subject to legal or technical restrictions.

Main producers of information are the citizens who consciously or unconsciously add information to these databases. the most successful project is OpenStreetMap that up to date, counts 10.729.032 users and 23.604.230.005 GPS points (*OpenStreetMap Statistics*, n.d.). Other VGI projects are Wikimapia, Map Maker, Here Map Creator, Map Share and Waze.

Citizens can actively or passively add information to the map. The active mode is when people are aware of updating the map by participating in some campaigns aimed at updating databases. The passive way, on the other hand, takes place thanks to the GPS inside mobile phones, when georeferencing any post on social media, for example (See et al., 2017). These maps also contain so-called 'framework data', that is the 'most common data themes that users of geographic data need', which can 'typically include seven framework data themes: geodetic control, orthoimage, elevation, transport, hydrography, governmental units and cadastre. These data represent relatively static phenomena and are commonly used for administrative programs, wayfinding, geopositioning, geotagging, and other popular services, so they have been a traditional target of government data production" (Elwood et al., 2012).

Regarding the correctness of data, citizens tend to enter or correct only the data they really know, generally related to the area in which they live. Many institutions that produce geospatial data have espoused the cause of OpenStreetMap, such as for Italy Portale Cartografico Nazionale (PCN), since 2010, makes its images available (*Italy/PCN - OpenStreetMap Wiki*, n.d.). Several studies (Borkowska & Pokonieczny, 2022), (Minaei, 2020), (Dorn et al., 2015) have shown that from a geometric point of view, the information contained in OpenStreetMap databases are quite correct, especially regarding buildings and the transport network. Another important fact concerns the accuracy, which increases proportionally to the urbanization of the area. Accuracy of data is one of the requirements also expressed in ISO 19157:2023 geographic Information - data quality. According to this standard, the quality of geospatial data is based on several characteristics:

- Completeness: presence of values describing different characteristics;
- Logical Consistency: degree of adherence to the rules of the data structure (documented and named);
- Positional Accuracy: accuracy of the measurement between the given position and the position accepted as true within a reference system is. For Global Navigation Satellite System (GNSS), it is within 2-3m.
- Thematic Quality: accuracy of quantitative attributes and the correctness of non-quantitative attributes and feature classifications and their relationships.
- Temporal Quality: the quality of temporal attributes and temporal relationships of features

2.2 Open Street Map as a reliable data source

Due to its large diffusion, the study proposes OpenStreetMap as a reliable and scalable data source. The project started in 2004, so it developed right at the same time as the evolution of crowdsourcing concepts. This study takes all the urban data from OpenStreetMap, which can in fact export part of the whole map. The exported file can also be used as a base map within GIS software. The .osm format is proprietary, but it is written in XML so it is interoperable due to an expandable language (Behr & AGSE. 5 2012 Stuttgart., 2012).

Although the idea is that anyone can insert new information into this map, OpenStreetMap is not included in the more than 70 standards of the Open Geospatial Consortium (OGC). Voluntarily OpenStreetMap does not conform to the standards because its purpose is not to be a standard but only to be a map containing geospatial information.

Despite this fact all OpenStreetMap data can be used and possibly even transformed according to the standards, in fact there is third-party software that allows to read .osm files and transform them into shape files.

OpenStreetMap has its own data structure comprising three geometric features (Nodes, Ways, and Relations) plus an object information feature (Tags) (Vargas-Munoz et al., 2021).
Nodes are the main element in the data structure and represent symbols. A node is a transposition of a point of interest on the earth. Several nodes together form a way, which can be open (polyline) or closed (polygon). An example of a polyline can be a road or a river, while the most illustrative polygon is a building. At least two nodes are needed to create a polyline, while three nodes are needed to create a polygon. It is therefore possible to relate several nodes to create a road, but it is also possible to relate geometric objects with information objects (tags).

Tags consist of two items 'key-value' where the key describes the type or category, and the value is the specification of the key. The insertion or modification of tags is free, in fact although OpenStreetMap has a defined structure of tags, it leaves the user the possibility of adding different tags.

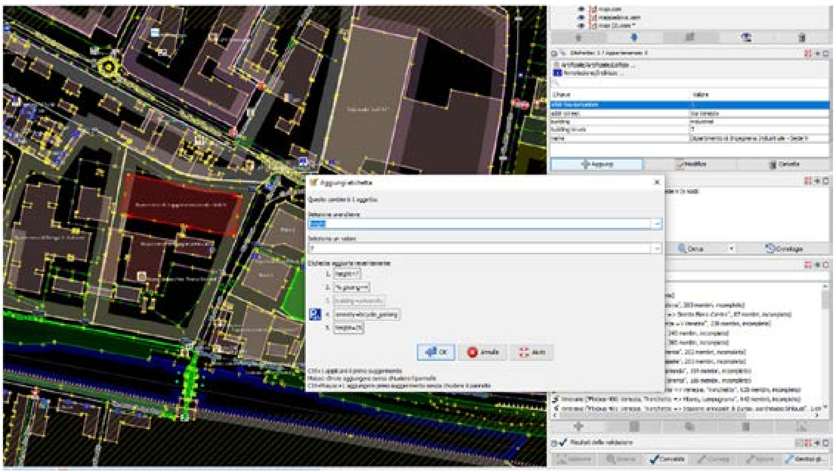

Fig.1: Adding a tag with JOSM.

Unfortunately, the estimates clam that less than 3% of the objects have the height key filled in and very often also wrong. Height is the typical datum that must be entered by the user to be correct, it cannot be taken from satellite orthophotos. Calculating this data could be difficult to obtain especially if the building is tall, which is why the study (Bshouty et al., 2020) of has created an app "OpenStreetHeight" that can calculate the height using a photograph. The height for the buildings, in the selected area, was not present within the .osm file but was visible through the OSMBuildings application. This site, written in Java, shows at the three-dimensional level the 2D map of OpenStreetMap According to what has been said so far, if a data is wrong or missing everyone can change and update it, and that is what has been done. To be able to modify the data there are several editors. There are both computer and telephone applications. The best known and most widely used are JOSM (Java OpenStreetMap) and Potlatch (Neis & Zielstra, 2014), both are computer applications. Through these applications, the map can be viewed and edited. Adding the data, using JOSM, is very simple just import the map and selecting the building polygon add the tag.

2.3 Generation of the model

To create the model of the case study area, the initial step involved the editing of the source OSM file. In fact, certain unnecessary data had to be modified or removed from the starting .osm file. The primary data was generally accurate, except for building heights, which were often incorrect, listed as a default "3 meters" when not available.

To acquire accurate data, several methods were considered, also including LIDAR technology (Manni et al., 2022). LiDAR sensors can gather highly precise and detailed elevation data. These advanced sensors emit laser pulses toward the Earth's surface and measure the time it takes for the laser to return after hitting an object or the ground. By analyzing the return time and the wavelength of the laser, LiDAR systems can calculate the distance between the sensor and the target surface with exceptional accuracy. In any case, it is important to have adequate equipment to carry out these surveys, and for that reason, in this case, building heights were manually calculated by cross-referencing data like the number of floors, using JOSM to modify and delete data. Additionally, two new tags were inserted:

- Transformation coefficient: which represents the percentage of façade or building transformability, indicating the freedom to incorporate new installations on surfaces or interiors.
- % glazing: which represents the total glazed area relative to the total area.

Correct values for these new parameters will be calculated for each building and replaced together with the starting information. Each element in the OSM file has a unique ID number to identify it. The default value is 1 for façade transformability and 0 for glazing.

A generative script developed with Grasshopper's Urban tool generated building volumes starting from OSM metadata and including the urban geometry of roads and external spaces. Each building is represented as an extrusion of its planar geometry. The source file also contains other information, such as the number of levels, function type, and structure identifier, unique to each building.

Climatic and environmental conditions are gathered by .epw file. Ladybug offers a library of data collected from weather stations worldwide, downloadable from their official website (*EPW Map*, n.d.). For the case study, data from the Treviso airport weather station was used due to a lack of specific data for the Padua area. The available data is for year 2020, and the simulations presented focus on the entire month of July 2020.

Before conducting simulations, the presence of greenery and trees must be considered, as they significantly impact solar potential and act as crucial mitigating elements. Therefore, the 3D geometric model was supplemented with the modeling and placement of trees and green elements based on their actual arrangement, height, and leaf density, utilizing a site survey and satellite images for accuracy.

2.4 Solar potential study

Once the basic geometric model is prepared and enriched with additional information, the analysis of solar potential can commence using various available tools, both in GIS environments and beyond. In a comparative study conducted by (Giannelli et al., 2022), five main tools, including GRASS GIS, ArcGIS, SimStadt, CitySim, and Ladybug, were assessed by comparing their simulation data with ground truth data obtained from a weather station (Jakica, 2018), (Peronato et al., 2018). Among these tools, Ladybug was found to be one of the most accurate for solar radiation studies, sky view analysis, sunlight hour modeling, and more (Freitas et al., 2015). Therefore, it was chosen as the basis for the research work in this study.

However, a notable challenge faced by all the tools, including Ladybug, is that the data obtained through simulations are related to simplified surfaces that do not correspond to the real conformation of buildings. Consequently, they may not provide reliable estimates of the exact solar potential, as factors such as surface conformation and the percentage of glazing can significantly impact the results. For instance, certain surfaces may not be suitable for the installation of new energy systems throughout the entire area (Esclapés et al., 2014). The issue arises as simplified models treat all surfaces uniformly, considering them flat and non-glazed facades.

To address this problem, the study aims to introduce coefficients that can account for these specific building characteristics and rectify the results obtained from the simulations. By identifying and incorporating these coefficients into the analysis, the study seeks to obtain more realistic and reliable data with minimal additional complexity. This process involves coding in Grasshopper to automate the identification and application of the coefficients to the simulation results, streamlining the evaluation process (Assouline et al., 2017).

2.5 Energy Potential study

The definition of the energy retrofitting potential of a building is based on the development of a method which allows the cataloguing of technical elements and their subsequent differentiation through the analysis of geometric, aesthetic and technological factors and the relative retrofitting potential. The main objective of this research activity is to develop a simplified type of rapid assessment model about building technical elements, whose horizontality allows the extension of the experimental scheme to the entire building system to evaluate its potential and criticalities and to direct a specific renovation process. The formulation of a percentage score, an indicator of the building retrofitting potential, constitutes the tool for pre-evaluating the effectiveness of its efficiency and for comparing buildings belonging to the same stock to identify a design strategy that is convenient both from an economic and energy point of view.

The structure of the methodology is based on the definition of the upgrading potential, which quantifies the possibility of increasing the performance level of a technical element by implementing specific retrofitting measures. For example, the presence of geometric and aesthetic constraints could significantly limit the building transformability. Although the upgrading potential is directly focused on the element itself, the definition of retrofitting potentials introduces a preliminary assessment of possible interventions.

Once virtual potential for improvement has been defined, it is necessary to introduce the concept of transformability, which indicates the readiness of a technical element or a building to accommodate a technological solution aimed at increasing the energy efficiency. Thus, this parameter represents a tool to moderate the value assumed by the potential according to the real possibility of intervention. The definition of this parameter considers geometric, aesthetic and technological features of each technical element. In fact, the transformability coefficient (T) is the result of geometric mean (Equation 1) of the geometric (T_G), aesthetic (T_A) and technological transformability (T_T).

$$T = \sqrt{T_G \cdot T_A \cdot T_T} \quad (1)$$

Therefore, the combination of the virtual potential and transformability rate into a single index, called effective potential for upgrading, guarantees the moderation of technological element potential as a function of its transformability.

To define effective potential rate, this method involves a careful process of analysis of the specificities that distinguish each item. Both transformability and upgrading potential are subjected to the assignment of a score, a coefficient between 0 and 3 to each index. A coefficient of 3 corresponds to the maximum possibility of intervention to which a technical element can be subjected. On the other hand, a value of zero is determined by the impossibility of intervention: in the case of potential, zero indicates the absence of actions that increase the energy performance of a building component (if it is already particularly performing), while a zero transformability derives from the presence of constraints that inhibit any design strategy. Depending on the type of component, the meaning of the rates changes according to the peculiarities.

The decision to use a classification system with a peer number of coefficients stems from the desire to reduce the possibility of a high percentage of components falling within the median.

At the same time, this research work proposed the decomposition of the building system provided for by UNI 8290 and identifies five technical elements, such as opaque vertical components and windows, opaque horizontal components and heating systems. In addition, the methodology included a census of these elements to determine their profile in terms of energy potential. The entire set of examples is the result of research into sector manuals and direct observation of buildings in nearby cities: in particular, the attempt to grasp the complexity and variety of technical elements is one of the main objectives of this compilation. However, it must be stressed that the definition of building archetypes is a subject that will be further developed to capture the diversity of the building sector.

3. EXPERIMENTATION

The research work, for the solar potential study, involved the analysis of two significant buildings within the study area, focusing on their geometric and solar aspects. The first building, primarily used for offices, had a rectangular floor plan with an overall height of 30m. Its facades featured a series of pilasters, creating a rhythmic pattern of window openings. The second building, with the university department of industrial engineering laboratories, had a rectangular plan with a height of 9m. Its facades were predominantly composed of windows, forming an overlapping grid pattern. The roof of this building had a distinctive stepped pattern.

To analyze the solar potential of these buildings, two models were developed for each, a simplified model, and a more detailed one. Ladybug for Grasshopper was used for the simulations to obtain the solar potential values for each facade. The factors that significantly influenced the actual solar potential were the percentage of windowed and opaque surfaces and the conformation of surfaces susceptible to transformations. The shading factor was already considered by Ladybug, and the presence of elements like balconies would be accounted for in the detailed model.

An equation (Equation 2) was derived to relate the real solar potential value (SP_r) to the simplified solar potential value (SP_s), the percentage of the opaque area ($\%op_{area}$), and the transformation coefficient (T_{coeff}). The simplified solar potential value was obtained through Ladybug simulations on the simplified model. The opaque area percentage was calculated from geometric analysis using software like AutoCAD. The transformation coefficient was derived by using an inverse equation based on the real solar potential value from the detailed model.

$$SP_r = SP_s \cdot \%op_{area} \cdot T_{coeff} \quad (2)$$

The data for the transformation coefficients, opaque area percentages, and glazing percentages were then included within the .osm file to enrich the information for each building. The JOSM software facilitated editing the .osm file to create new categories of parameters and associate their values with each building. For simplicity, a single parameter was associated with each building for the new data categories, taking the average values for each facade and roof to account for varying conformations.

By applying the new coefficients to the data of the simplified solar potential, a more accurate estimation of the solar potential value was obtained, considering the actual building conformation. The additional data calculated using this methodology was inserted into the .osm file for each building using specific identification codes. The file was then exported in .xml format, allowing the GIS environment to read the new data along with the existing data in an open-source format. This approach enables the creation of more realistic territorial models, providing more reliable information on solar potential at a granular level.

The energy potential research activity involves the transformation of the initial qualitative approach, linked to the formulation of a rehabilitation potential index, into a scientifically based methodology. To achieve this, the development of energy simulations made it possible to provide a numerical basis for the initial survey. In this way, the results obtained are crucial to the establishment of the methodology, like the definition of the rehabilitation potential. Specifically, the aim is to quantify the reduction in energy consumption resulting from the implementation of a given retrofitting measure affecting a specific component, leaving the conditions of the other technical elements unchanged. The experimental activity leads to a ranking of the efficiency measures, expressed in terms of energy demand reduction. Thus, it will be possible to relate the actual improvement potential of each technical element to the actual energy footprint assumed by the same. This phase is not an integral part of the methodology, but it is functional to validate its results for subsequent applications.

The verification of the previously assigned virtual improvement potential rates required the development of energy simulations using the EC700 software supplied by Edilclima. Edilclima is one of the main Italian software packages for calculating energy diagnoses. The choice of this calculator is due to the high interoperability between the BIM modelling, carried out in Revit, and the energy simulation software. In fact, the introduction of EC770 (the plug-in provided by the company) makes it possible to derive a large part of the input data for determining the energy performance of a building from the architectural model, speeding up the process.

Moreover, the procedure has introduced a series of energy improvements, each of which is intended for one building component. The decision to use this specific method, which is very different from the usual practice, stems from the desire to be able to calculate the influence of the improvement in the efficiency of a specific technical element on the overall behavior. Several architectural models have been defined in the process to group together the building types studied during the survey phase and, therefore, to evaluate the energy savings percentages by carrying out a considerable number of energy simulations. Specifically, for each macro-category of technical element, a common design state was identified to compare the percentages obtained.

For this purpose, it was considered appropriate to adopt an extremely simplified architectural model. A rectangular building with a side of 10x6 meters, developed on two levels, was implemented in Revit. The floors have the same layout and contain only one room. The construction characteristics are the most common in Italy. It is a load-bearing masonry construction, with brick floors and roofs. The energy performance is particularly poor. To determine the actual impact of a technical element on the overall energy savings, it was considered appropriate to vary the energy characteristics of the considered component, while leaving the other parts of the building organism unchanged. An attempt was made to reproduce the most representative cases of the previous survey.

Four possible types of heating systems were identified: radiators, radiant floors, fan coils, full-air system.

Two boiler variants were associated with each type, such as a traditional boiler and a condensing boiler. The energy retrofit intervention includes the replacement of the central heating system with a heat pump and the installation of a photovoltaic system with a total power of 4.5 kW, while keeping the envelope performance unchanged. The following results were obtained:

Table 1: Schematization of the reduction in energy consumption due to heating system retrofit

Type of plant	Heating generator	EP pre intervention	EP post intervention	Energy saving
Radiators	Boiler	318,86 kWh/m^{2}year	99,00 kWh/m^{2}year	69%
	Condensing boiler	294,06 kWh/m^{2}year	99,00 kWh/m^{2}year	66%
Radiant heating	Boiler	302,93 kWh/m^{2}year	99,00 kWh/m^{2}year	67%
Fancoil	Boiler	305,27 kWh/m^{2}year	118,60 kWh/m^{2}year	61%
	Condensing boiler	281,60 kWh/m^{2}year	118,60 kWh/m^{2}year	58%
Air system	Boiler	319,07 kWh/m^{2}year	67,14 kWh/m^{2}year	79%
	Condensing boiler	290,67 kWh/m^{2}year	67,14 kWh/m^{2}year	77%

Therefore, it can be concluded that the maximum reduction in energy consumption is obtained from the efficiency of the air system, which is over 70%. This result confirms the value of 3 of virtual potential given to the system under consideration. Then, this reasoning was extended to the five technical elements to obtain a complete view of the thermal behavior of a typical building.

Furthermore, the values obtained were used as a tool to calibrate the energy potential values initially assigned based on qualitative assumptions about the energy behavior of each component. This phase was supported by the analysis of the results in Excel. In fact, the formulation of a classification of the reduction in consumption attributable to the improvement of the different types of each technical element made it possible to place the corresponding potential values within four energy saving ranges.

During the experimental stage, the method was applied to a specific case study. The building is one of ATER's buildings of Padua and it is in Ferdinando Coletti Street. It is an apartment block, developed on four levels and divided into three different staircases. Each staircase serves a total of eight residential units, consisting of approximately 45 sqm, whose layout is repeated on all four levels. The size of the typical apartment is rather humble: it consists of a living area with a kitchen and a separate sleeping area, which is served by bathrooms. The building has undergone various renovations over the years, which have not ensured its good state of conservation. In the 1970s, a refurbishment was carried out with questionable results: the total renovation of the facilities allowed the construction of an internal toilet for each flat. Moreover, the energy simulation confirmed its energy-intensive nature. The absence of insulation and technological solutions ensures the veracity of the results.

Established the poor energy performance of the current state, two different intervention scenery could be identified. Specifically, the first is related to maximizing the heating system efficiency, while the second is related to maximizing the insulation of the envelope to reduce dispersion.

The first scenario concentrates almost all resources on the energy retrofitting of the heating system, followed by limited insulation measures. The retrofit action foresees the introduction of renewable energy sources and the installation of a heat pump generator and a radiant floor, after the demolition of the existing flooring with a consequent increase in height, but it is compatible with the functional-spatial characteristics thanks to the high room heights. The autonomous system configurations remain unchanged. The installation of a centralized photovoltaic system on the roof provides a large proportion of the energy required by the new heating plant. Once the retrofit intervention on the installation system had been defined, the discussion focused on evaluating the reduction in energy demand caused by the insulation of the envelope. Thus, it is possible to separate the contribution to the efficiency of envelope structures from the overall behavior. These retrofitting actions include the insulation of opaque components and the replacement of windows to comply with the transmission limits imposed by Italian regulations.

The second scenario focuses attention on increasing the insulation of the envelope and, regarding the systems, replacing the existing generator with a condensing boiler and the existing heating terminals with a radiant floor to ensure proper operation at a lower temperature. The individual system configurations remain unchanged.

4. ANALYSIS AND EVALUATION OF RESULTS

During the final stage, it becomes crucial to evaluate the obtained solar potential data to determine if there are significant differences between the results obtained from simplified models and detailed models, and whether the simplified data is adequate for the evaluation purposes, especially when considering the inclusion of a new system. For instance, upon analyzing the data regarding the total solar potential of some of the buildings present in the area, it was measured a considerable difference corresponding to a potential drop of about 25%. The discrepancies in the results are quite significant, emphasizing the importance of model enrichment to avoid overestimation of solar potential when relying solely on basic models for evaluation. The detailed models provide a more accurate representation of the solar potential, making it evident that the use of simplified simulations alone may not suffice for precise assessments and decision-making regarding the implementation of new energy systems.

The application of the EP method to the case study made it possible to identify its main weaknesses and to optimize its use. In particular, the conversion of the numerical scale with values between 0 and 3 into percentages required various experiments and subsequent adjustments. The initial approach was to proportionally convert the numerical indices of transformability and upgrading potential: however, the implementation of the method highlighted that situations characterized by low transformability were particularly disadvantaged in the calculation of potential for energy redevelopment. The reason can be found in the series of multiplicative operations that lead to the definition of the upgrading potential: in fact, a low potential value is obtained starting from average values assumed by the transformability and the virtual potential. The further multiplication between the effective potential and the technical element weight contributes to a further reduction of the achievable energy savings, making it incompatible with the results of energy simulations. The first attempt to transpose the transformability and the virtual potential was carried out independently of the type of technical element, disregarding the results of the energy model. For this reason, it was necessary to completely revise the entire transformability allocation matrix, calibrating the percentages for each technical element. To facilitate the implementation of energy retrofitting measures, it was appropriate to shift the entire numerical scale to values greater than 70 per cent, thus projecting values in the range between 70 and 100 per cent. The agreement between the results of the fast method and the energy simulations was the basis for the choice of the percentage range.

The graphs below show a comparison between the results obtained by using the methodology, the energy model and the projection of the energy savings obtained by the efficiency of a model type (with construction characteristics very closed to the case study), representing the research building. In the first scenario, the analysis of the deviations shows a maximum deviation of 11%, related to the heating system.

On the other hand, in the second scenario, a maximum deviation of 24% is reported for the insulation of the vertical perimeter walls. The reason for this difference can be found in the proposed interventions: in fact, the walls of the case study have external aesthetic reliefs that are incompatible with the installation of an external insulation system. The insulation is therefore provided internally. On the other hand, the simplified model proposes the external technological solution which, for the same thickness, leads to a better energy performance thanks to the correction of thermal bridge. Where:

- A represents the gap created between the reduction in consumption derived from the methodology and the energy simulations.
- B represents the gap created between the decrease in consumption derived from the methodology and the projected decrease in consumption.

- C represents the gap between the reduction in consumption derived from the energy simulations and the projected reduction in consumption.

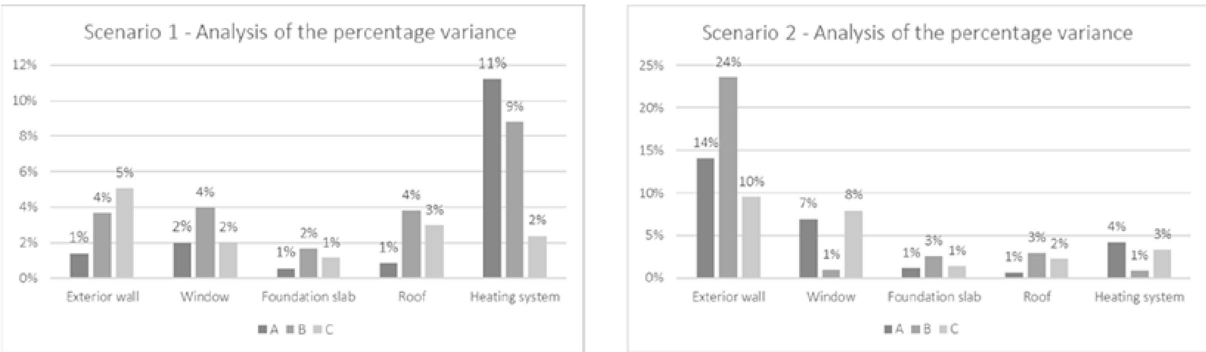

Fig.2: Comparison of methodology results of heat pump systems (scenario 1) and condensing boiler (scenario 2)

5. CONCLUSION AND FUTURE WORK

The innovative aspect of this process revolves around information-related elements, as modern tools process geospatial data that can't be modified based on typological criteria to enhance analysis results. The provided proposal delineates the methods to attain these objectives, approached from two key angles. Firstly, from a disciplinary standpoint, it involves the establishment of transformation coefficients. Secondly, from an informational perspective, it revolves around fostering the interoperability of solar potential reduction factors.

To apply this methodology to various building contexts and urban environments, it becomes crucial to categorize different case studies of typical facades and roofs, examining the similarity between buildings. This allows for the creation of a set of moderating coefficients and parameters associated with the urban environment, considering the structure's form and glazing percentage. For scalability, the process of creating a solar map at the neighborhood level should be as automated as possible to establish urban environment parameterization standards.

One limitation of this approach is that when selecting corrective coefficients on a large scale, it requires more time for context analysis and relies on source materials such as aerial photographs or files that identify the differentiation between glazed and opaque surfaces, which may be challenging to obtain. Moreover, it would be interesting to extend the study further by assessing how much energy could be generated from various PV systems to determine the percentage of energy needs that these systems could cover for the buildings in the area.

The study was conducted in a small area of Padua, but with the necessary adaptations, the data could be replicated across the entire city map. This would enable the integration of the findings into the OpenStreetMap project, expanding the database with valuable information on Solar Potential for the entire city. It is evident that the results show that the methodology is validated by the energy simulations by analyzing energy potential method. In fact, the percentage deviation of the values is around 10%, a percentage that can be considered acceptable in a preliminary assessment. Therefore, the application of the method allows a quick screening within a building stock, identifying the buildings responsible for greater energy savings.

Specifically, it was possible to highlight that heating systems constitutes the most decisive factor in the process of formulating the design hypotheses: thus, it is not possible to disregard the evaluation of plant transformability that, in the first instance, governs the declination of the retrofit intervention. This assumption derives from the fact that, with the same envelope, the replacement of a traditional generator with a heat pump, the installation of a radiant floor system and a photovoltaic system cause a decrease in energy consumption of approximately 70%. The discriminating factor is the possibility of installing renewable energy production systems, which make the thermal behavior of the envelope take second place since the energy produced is largely free. Therefore, it can be said that maximizing plant efficiency is the winning strategy. Where systems are characterized by good performance, it is more convenient to intervene on the envelope insulation.

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IMPLEMENTATION OF BUILDING INFORMATION MODELING BIM FOR ECONOMIC SUSTAINABLE CONSTRUCTION MINIMIZING MATERIAL WASTE IN TERMS OF VALUE ENGINEERING

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ABSTRACT: *The construction industry consumes a large amount of raw materials and produces large amounts of carbon dioxide emissions. However, studies have shown that philosophies alone are not efficient in solving problems in the construction industry. They must be supported by new tools and methodologies. Therefore, this study aimed to achieve a more sustainable building field by integrating BIM technology and value engineering principles in the management of building materials. to achieve the highest possible consumption of environmental resources and materials through value engineering. The methodology employed in this study was to develop a material waste management system for construction projects. Starting in the early design phase, develop a decision-making process for selecting the optimum floor tile size according to room dimensions. Some materials, such as floor tiles, wooden panels, and marble, can be used more efficiently using BIM and scheduling tools. Floor tiles are essential finishing materials in the AEC industry. The initial findings outline the benefits that can be obtained by using BIM tools to achieve waste minimization through value engineering principles by creating an automation process to choose the best floor tile size according to the space width and length and minimize the percentage of cut tiles to the total number of tiles that are used in the space. This provides a game-changing solution for construction stakeholders.*

KEYWORDS: *Building Information Modeling, Value Engineering, Sustainable Construction, Material Management, Construction Site Management, Architectural Engineering and Construction.*

1. INTRODUCTION

The construction industry is a critical sector in terms of economic sustainability. This enhances economic growth because it affects other economic areas. Appropriate building material selection and recommended construction details significantly affect the project cost. Moreover, their consumption value is approximately 40% of a project's total cost [3]. The designer ensures that the materials used in the proposed design are chosen accurately.

Floor tiles are major building materials widely used in the Architectural, Engineering, and Construction (AEC) industry. Moreover, it is used in every project with different materials and sizes. is also an essential material in architectural decoration, and its annual consumption worldwide has reached billions of square meters. For example, ceramic tiles, a type of floor tile, require high-temperature firing in factories to produce them, resulting in high energy consumption and significant pollutant emissions., thereby posing a serious threat to human health. The annual consumption of ceramic tiles reached 13 billion square meters by 2020, and more than half were used as floor tiles [6,7]. Improving the efficiency of floor tile application plays a critical role in promoting sustainable development in the AEC industry. Previous studies have shown that improving accuracy, effectiveness, and comprehensiveness may be an effective way to improve project benefits from the design perspective [6].

Compared with refined design, the waste rate difference of building materials caused by different design approaches can be as high as 41% in general architectural construction, and the difference in construction labor resource waste (e.g., rework) also shows a positive correlation [8].

In the architectural project, the architects chose the floor tiles according to the color and design, regardless of the size of the tiles and the wastage of cut tiles. Taking into consideration that Most tile producers and suppliers have different sizes for tiles of the same design and color. In theory, layout design requires architects to accurately plan the laying and cutting of materials. The design should include uncut and cut tiles and provide accurate graphics and figures for the following steps to achieve lean material management [9].

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Aya Ali Shihata, Mohamed Anwar Fekry, Wessam Hamdy Abbas, *Implementation of Building Information Modeling (BIM) for Economic Sustainable Construction Minimizing Material Waste in Terms of Value Engineering,* pp. 1033-1041, DOI 10.36253/979-12-215-0289-3.103

Therefore, the main objectives of this study were as follows:

- To optimize the waste of floor tiles in construction projects from the early design phase.
- Choose the best flooring tile size for the room dimensions to minimize the waste ratio of the flooring tiles.
- Create a practical method for selecting the optimum floor tiles.
- To reduce the time required for technical office engineers in the takeoff process.

The optimization process is performed through the integration of the Value Engineering (VE) principles with Building Information Management (BIM) as a tool to input the data and the dimension of the space as parameters, input the different optional sizes of floor tiles, and apply the VE principles and equations.

1.1 BIM and VE integration approach

A project's success and higher market value (fulfilling the owner's specifications) depend on controlling the construction schedule and costs. To reduce the overall costs, stakeholders have increasingly been used in construction projects. The early project phase offers a great opportunity to use BIM to streamline VE. A bibliometric analysis was performed by Baarimah et al. in 2022 to determine the benefits of combining BIM and VE. The findings demonstrate that VE and BIM support rising prominence as mainstream subjects related to the building industry and decision-making around cost-earned value. The evaluation of generated alternatives using predetermined criteria is the most important stage in VE applications. Stakeholders can use multi-attribute criteria to integrate created models by designing an automated method to assess and contrast these options.

1.2 Value Engineering (VE).

Value Engineering (VE) is a proven management approach in the (AEC) industry that is used to improve the functioning of projects and eliminate unnecessary costs. Because the construction industry has faced various challenges in reaching a project's high value on time and within budget, VE has been applied in numerous countries around the world for half a century [9]. VE has become an integral part of the development of many projects' development [10]. Surveys have reported that VE can save as much as 5–10% of construction project costs [11].

The VE study procedure called the VE job plan, is a systematic problem-solving technique comprising the following phases: information, function, creativity, evaluation, development, and implementation. Among these phases, the creativity phase, followed by function analysis, is the most crucial for generating innovative ideas that require existing information and experiential knowledge from past VE projects [12].

Value = Function + Quality/ Cost

Where:

Function = The specific work that a design/item must perform, which must be the same for all the options of floor tiles

Quality = owner’s need, which is the percentage of cut tiles.

Cost = life cycle cost of the product. Moreover, the additional cost of the wastage of the materials

Assuming that the materials are compared, they have the same quality of manufacturing with the same design, color, and materials of different sizes, for example, the same ceramic tile with different sizes only. In this case, the tiles have the same function and quality.

1.3 The current approaches to selectin floor tiles

In most cases, architects choose floor tiles in the conceptual phase of the design by focusing on the type, color, and texture based on design principles, without paying attention to the importance of the floor tile size in the waste management process in the early decision-making stage of the project. Subsequently, shop drawings were drawn without providing the exact tile requirements. Therefore, quantity surveyor engineers estimate the exact number of floor tiles, including uncut and cut tiles manually from shop drawings, which requires considerable effort and time.

For these procedures, it is difficult to produce a different shop drawing for each floor tile option to estimate the number of floor tiles with cut and uncut tiles, and to have a waste ratio to be able to choose the best floor tile size for each space.

As shown in Table 1, for two rooms with the same area and different dimensions, the default most commonly used ceramic floor tiles are 60 × 60 cm. There were different numbers of tiles used in the two rooms.

- The waste ratio for Room 1 was 14% and the total number of tiles used was 30.
- The waste ratio for Room 2 was 14% and the total number of tiles used was 40.

As shown in Fig. 1, the flooring tile layout plan for the default selection is 60x60 cm. There is a clear-cut tile in the two rooms, which can be avoided by using right-floor tiles.

Table 1: Parameters of default selection size.

	Area.	Length.	Width.	Long Ratio.	Total tiles.	Uncut Tiles.	Cut Tiles.	Waste Rate.
Room 1	120000cm2	400cm	300cm	1.3	35	30	5	14%
Room 2	120000cm2	600cm	200cm	3	40	30	10	25%

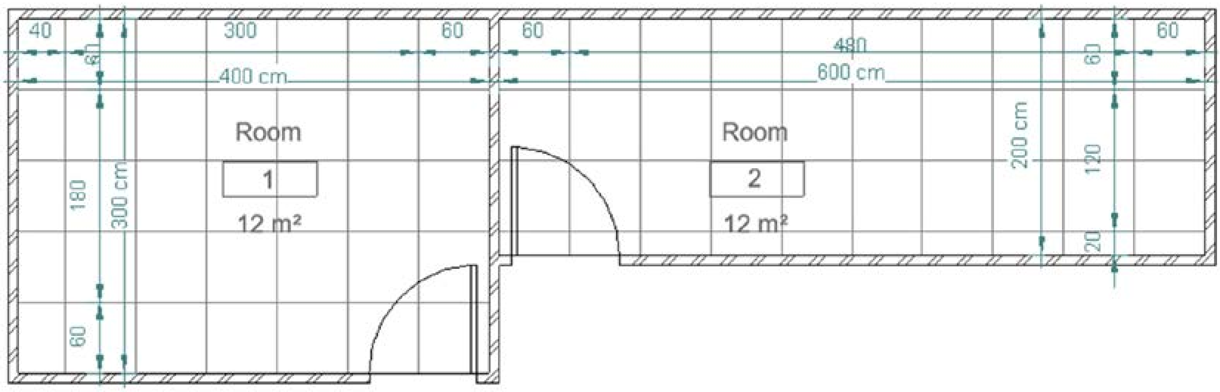

Fig. 1: Flooring tile layout plan for the default selection

2. RESEARCH METHODOLOGY

The purpose of this study is to develop material waste management for construction projects. Starting in the early design phase, develop a decision-making process for selecting the optimum floor tile size according to room dimensions.

As shown in Fig. 2, using a case study plan, this study focused on providing an automation framework according to the BIM model integrated with the VE job plan. The methodology focused on creating decision-making tools depending on the VE. The integration of the VE job plan and BIM into the framework through the optimization of the quantity of waste by applying the VE job plan through BIM tools to reach the optimum value by increasing the quality of the tile floor plan by decreasing the number of cut tiles to have as much space as possible with non-cut tiles, which is very visually comfortable, and decreasing the cost by choosing the optimum size of the tiles.

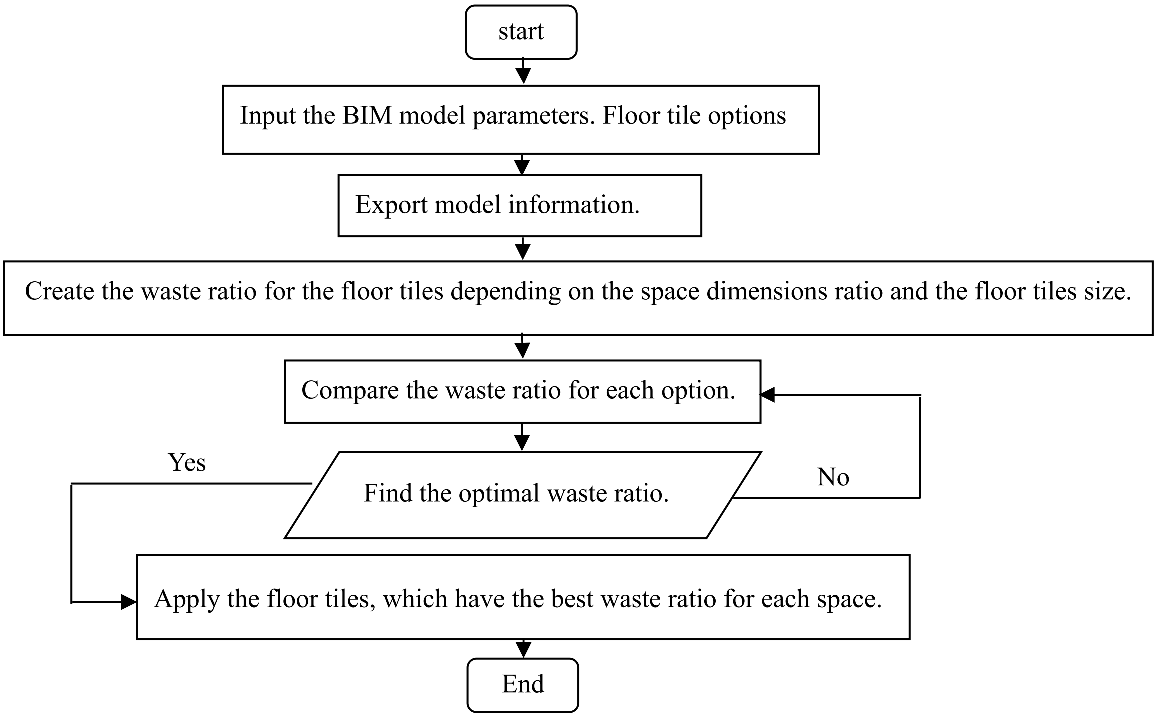

Fig. 2: The flowchart of the design decision-making tool

As shown in Fig. 3, the integration between the VE job plan and BIM optimization framework phase inputs the main parameters required for the floors.

- Function analysis: All the floors that were selected in the process must meet all the function requirements.
- Creativity Phase: Alternative sizer selection options.
- Evaluation phase: start to comprise the alternatives which had been chosen to meet the best quality and assess the risk for each option.
- Development Phase: Finalize the cost and schedule impacts.
- Implementation Phase: Initiate applying the optimum selection choice per quality and cost.

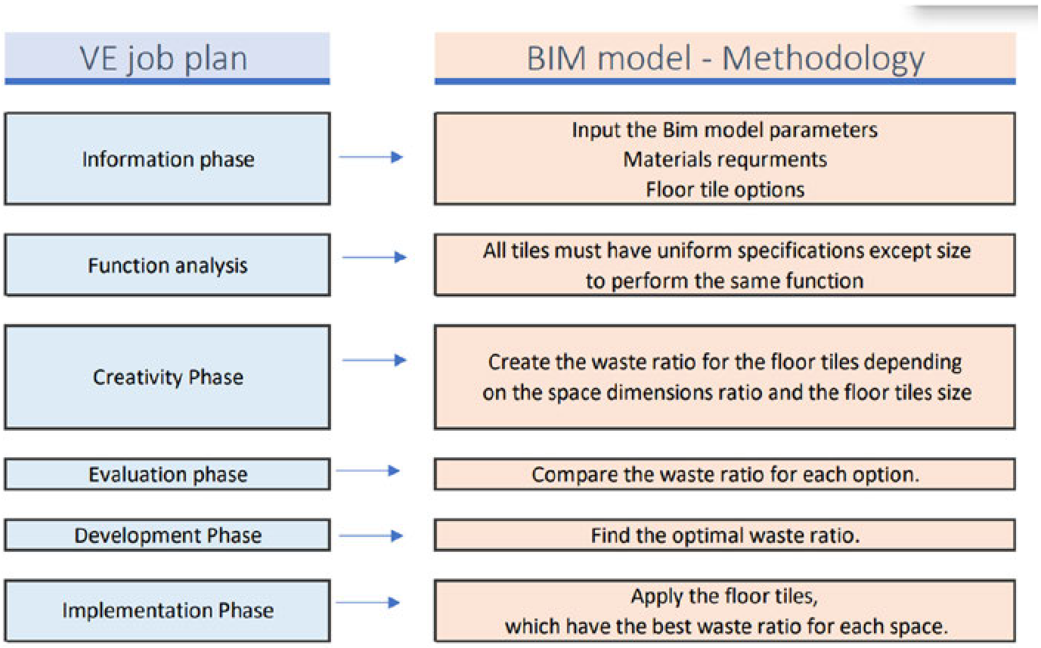

Fig. 3: The integration of the VE job plan and BIM into the optimization framework

3. CASE STUDY

Starting phase: Building the BIM model and inserting the floor tile options as parameters for each room, including the length, width, and dimensions of each floor tile option for each space in the model.

Fig. 4 shows a case study of two different rooms with the same area and different dimensions.

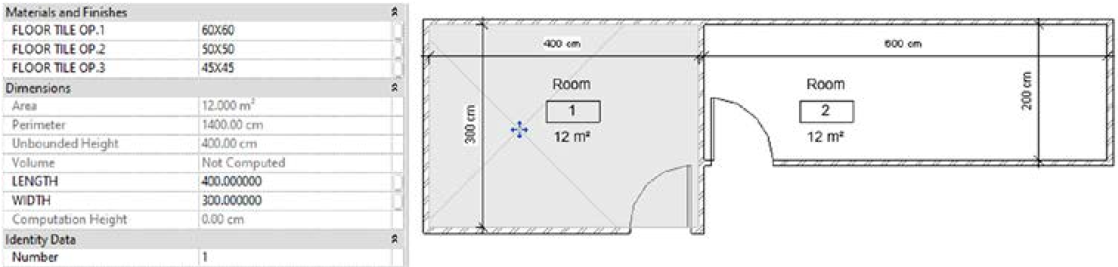

Fig. 4: the model instant parameter for each space

The next step is to create a Revit schedule for the instant parameter for each space, including the area of the room, length, width, and floor tile options. As shown in Fig. 5.

<FLOOR TILES OPTIONS>						
A	B	C	D	E	F	G
Name	Area	LR	WR	FLOOR TILE OP.1	FLOOR TILE OP.2	FLOOR TILE OP.3
Room1	12 m²	600	200	60X60	50X50	45X45
Room2	12 m²	400	300	60X60	50X50	45X45

Fig. 5: the model instant parameter for each space

Then export the Bim model schedule to an Excel sheet to apply the equations for each floor tile option, including the total tiles, uncut tiles, cuts tiles, and waste ratio.

The waste ratio was calculated according to the dimensions of the space and optional tiles, as shown in Fig. 6.

	TILE SIZE		ROOM DIMENTIONS		TILES IN X DIMENTION			TILES IN Y DIMENTION			TOTAL TILES	UNCUT TILES	CUTS TILES	WASTE RATIO
	LT=LENGTH OF TILE	WT=WIDTH OF TILE	LR=LENGTH OF ROOM	WR=WIDTH OF ROOM	UNCUT TILES	LR/LT	TOTAL TILES	UNCUT TILES	WR/WT	TOTAL TILES				
ROOM 1	60	60	600	200	10	10	10	3	3.33333	4	40	30	10	25.00%
	50	50	600	200	12	12	12	4	4	4	48	48	0	0.00%
	45	45	600	200	13	13.333333	14	4	4.44444	5	70	52	18	25.71%
ROOM 2	60	60	400	300	6	6.6666667	7	5	5	5	35	30	5	14.29%
	50	50	400	300	8	8	8	6	6	6	48	48	0	0.00%
	45	45	400	300	8	8.8888889	9	6	6.66667	7	63	48	15	23.81%

Fig. 6: the Excel sheet of the waste Ratio

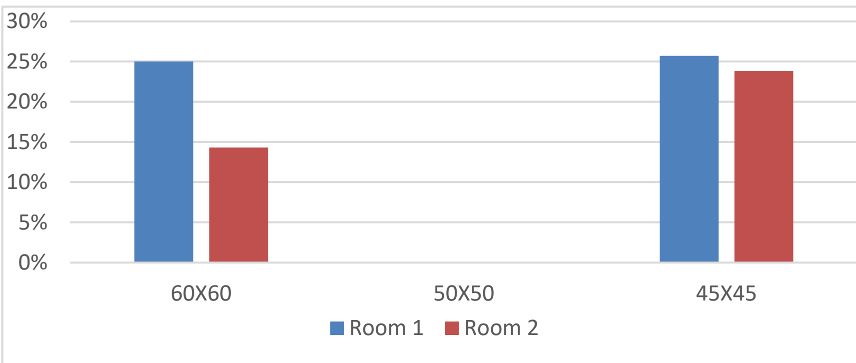

Fig. 7: Chart of waste ratio.

The schedule shows the results of the optional floor tiles, and the schedule shows the results for each space.

- The room 600 × 200 cm shows the following: the waste ratio of the tiling 60 × 60 cm is 25%, the waste ratio of the tiling, the waste ratio of the tiling 45 × 45 cm is 25.71%, and the best ratio is 0% for the flooring tiles 50 × 50.
- The room 400x300cm shows the following: the waste ratio of the tiling 60x60 cm is 14.29%, the waste ratio of the tiling, the waste ratio of the tiling 45x45 cm is 23.81%, and the best ratio is 0% for the flooring tiles 50x50.

Therefore, the optimum selection of the floor tile for the two rooms according to the design approach is 50 × 50 cm, as shown in the chart in Fig. 7.

The next step is importing the sheet excel into Revit using a dynamo script. The minimum waste ratio values were selected. Then, the selected floor tiles were applied to each space.

4. RESULTS AND DISCUSSION

The proposed workflow and decision-making tool for choosing floor tile size by integrating BIM techniques and VE principles generates the waste ratio for alternative floor-tiling sizes.

Rooms 1 and 2 have the same area (12 m2), but different widths and heights, which is used as an example of the current approach to floor tiles. After applying the research methodology and selecting the minimum waste ratio of the floor tile options, the waste ratios for Room 1 and Room 2 were reduced from 14% to 0% and from 25% to 0%, respectively. The total number of cut tiles and unused tiles is clarified in Table 2.

Table 2: Comparison between the default design approach and the optimized selection

	The original design				The optimized selection			
	Total tiles.	Uncut Tiles.	Cut Tiles.	Waste Rate.	Total tiles.	Uncut Tiles.	Cut Tiles.	Waste Rate.
Room 1	35	30	5	14%	48	48	0	0%
Room 2	40	30	10	25%	48	48	0	0%

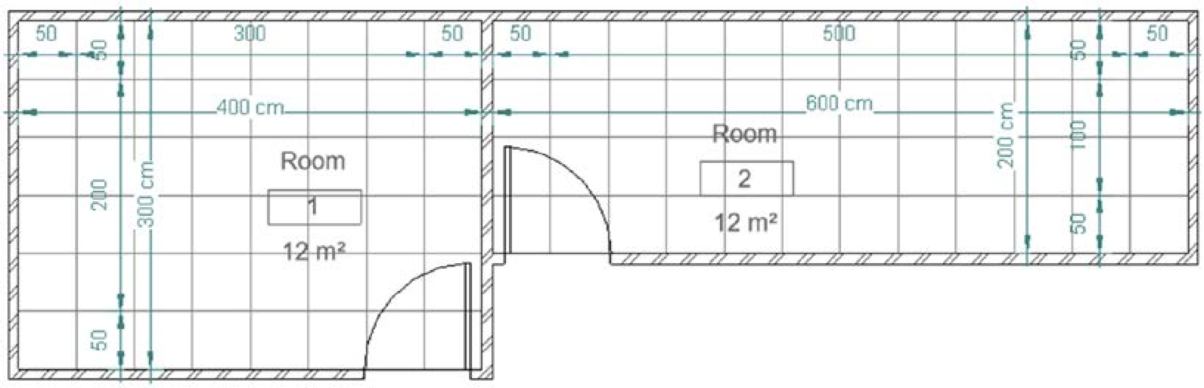

Table 2: Comparison between the default design approach and the optimized selection

As shown in Fig. 8, the floor tiling plan of the two spaces with the size of the selected tiles has a clear number of tiles with no cut tiles as a result of the proposed workflow, which is the optimum design of any space to have clear tiles with no cut tiles for multiple vectors, such as visual design-wise, sustainable to reduced waste ratio, and fast application.

Therefore, this design approach can be applied at different project scales with a large number of rooms to select the optimal floor tile size for each room and calculate the total waste ratio for all rooms that require the same floor tiles. Reducing the overall waste of flooring materials in the project eliminates the time required to apply value engineering principles in the project.

Selecting floor tiles in the AEC industry is a labor-intensive and time-consuming task. Architects often face difficulties in accurately creating shop drawings for floor tiles, owing to a lack of appropriate design tools. Consequently, they struggle to provide design support for subsequent stages, such as procurement and construction. This challenge becomes even more complex when architects need to incorporate waste reduction into their layout design. Consequently, the planning and cutting of floor tiles are typically performed extensively rather than precisely managed. This reliance on experience, rather than accurate calculations, leads to unnecessary material and labor wastage. To address this issue, we developed a workflow for generating accurate and comprehensive material waste rates.

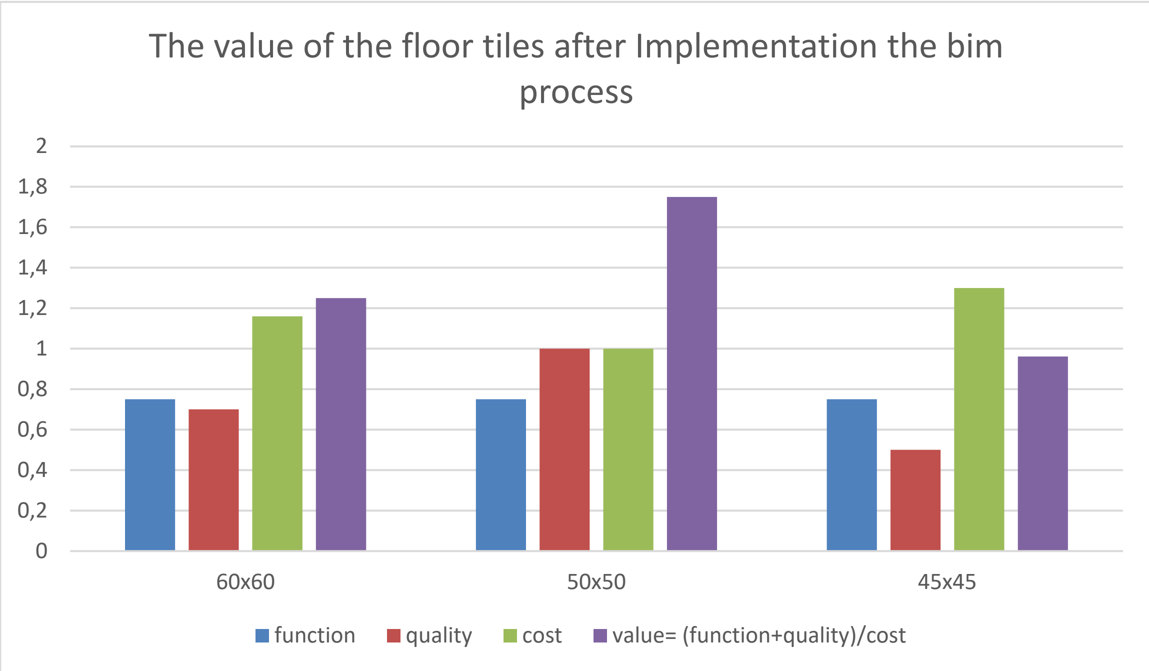

Fig. 9. The Result of the value engineering according to the integration of the Bim framework

5. CONCLUSIONS

This research proposes a workflow for selecting the optimized floor-tile size according to space percentage. The work limitation is on spaces with rectangular shapes with perpendicular angles, which is the most applicable space for material optimization in the VE process. All tiles must have uniform specifications except for size. The automation equation could be updated in future studies for application to regular spaces that are confirmed to have more than one rectangular shape by dividing the spaces into smaller rectangles.

The workflow integrates BIM and VE equations, enabling architects in the early decision-making phase of the project to automatically calculate the waste ratio of each floor tile size option by inserting the optional sizes, outputting the floor selection by the minimum waste ratio for each space individually, which significantly reduces the material waste, minimizing the time wastage of the quantity surveyor engineer surveying the quantity of tiles manually from the shop drawings, and calculating the exact number of uncut and cut tiles to enable the procurement engineer to order the correct amount of flooring tiles. This methodology is a step in waste management research to reduce the material-waste ratio and help technical office engineers to enhance the process of selecting and using flooring materials.

To enhance the entire tile design process, researchers proposed a workflow in the optimization process of floor tile planning to automatically generate the layout design of floor tiles, including uncut and cut tiles, after choosing the best tile size. [28]. Additionally, the two studies can be combined to form an integrated optimization process for the best tile planning.

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BUILDING ROOFTOP ANALYSIS FOR SOLAR PANEL INSTALLATION THROUGH POINT CLOUD CLASSIFICATION - A CASE STUDY OF NATIONAL TAIWAN UNIVERSITY

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ABSTRACT: *As climate change intensifies, we must embrace renewable solutions like solar energy to combat greenhouse gas emissions. Harnessing the sun's power, solar energy provides a limitless and eco-friendly source of electricity, reducing our reliance on fossil fuels. Rooftops offer prime real estate for solar panel installation, optimizing sun exposure, and maximizing clean energy generation at the point of use. For installing solar panels, inspecting the suitability of building rooftops is essential because faulty roof structures or obstructions can cause a significant reduction in power generation. Computer vision-based methods proved helpful in such inspections in large urban areas. However, previous studies mainly focused on image-based checking, which limits their usability in 3D applications such as roof slope inspection and building height determination required for proper solar panel installation. This study proposes a GIS-integrated urban point cloud segmentation method to overcome these challenges. Specifically, given a point cloud of a metropolitan area, first, it is localized in the GIS map. Then a deep-learning-based point cloud classification model is trained to detect buildings and rooftops. Finally, a rule-based checking determines the building height, roof slopes, and their appropriateness for solar panel installation. While testing at the National Taiwan University campus, the proposed method demonstrates its efficacy in assessing urban rooftops for solar panel installation.*

KEYWORDS: *Sustainable campus, renewable energy, point cloud segmentation, deep learning*

1. INTRODUCTION

One of the most critical and urgent challenges we face in this century is climate change, resulting mainly from human mass consumption of fossil fuels. Thus, replacing fossil fuels-based energy with renewable energy is a key solution to this problem (IPCC, 2022). Increasing the supply and usage of renewable energy relies on not only efforts by power producers and public sectors but also energy-heavy industries and private sectors. Hence, in recent years, many major corporations worldwide have announced their targets for decreasing carbon emissions and increasing renewable energy usage to fulfill their corporate social responsibility (CSR), and higher education institutions are no exception. Many universities worldwide have also announced their climate targets and planned to increase the usage and supply of renewable energy for their university's social responsibility (USR) (THE, 2022). National Taiwan University (NTU) also announced its carbon-neutral target and pathway in Nov 2021. To achieve this goal, the decrease in building energy usage and the increase in renewable energy are two key strategies. For the latter, how to install more solar panels and smart energy systems on campus is a key question to be explored.

To increase renewable energy supply, using spare spaces on building rooftops for solar panel installation is common in cities worldwide. Various factors affect the effectiveness of solar panel installation on the rooftops, including roof angles, shades created by nearby buildings or penthouses, and obstacles on the rooftops (Lin et al., 2022). To evaluate the potential of solar panel installation effectively, the collection and creation of digital data and models of study objects become critical (Sierra et al., 2022, Chen et al., 2023). Airborne laser scanning is a common practice to capture the basic outline of study objects (Wang et al., 2018). After segmenting the collected point cloud data via deep learning models, large-scale building reconstruction and automated extraction of building instances can be easily achieved (Huang et al. 2022, Feng et al. 2022).

This paper aims to analyze buildings' rooftops for solar panel installation through point cloud segmentation, taking National Taiwan University (NTU) in Taipei, Taiwan, as a study case. As the first university established in Taiwan, more than 100 buildings are on the main campus, built between the 1920s and the present. Large-scale building

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Aritra Pal, Yun-Tsui Chang, Chien-Wen Chen, Chen-Hung Wu, Pavan Kumar, Shang-Hsien Hsieh, *Building Rooftop Analysis for Solar Panel Installation Through Point Cloud Classification - A Case Study of National Taiwan University,* pp. 1042-1048, DOI 10.36253/979-12-215-0289-3.104

point cloud is collected using airborne LiDAR, and a commercial GIS tool, ArcGIS Pro, is used for further analysis. The analysis process and results are presented in sections 2 and 3, along with the challenges encountered. The research outcome can be a good reference for other university campuses which aims to use similar dataset for similar analysis. The main contribution of the paper is as follows:

- It proposes an end-to-end workflow for building rooftop analysis using point cloud data.
- It also proposes a simple and fast methodology for point cloud segmentation using commercial software tools such as ArcGIS Pro.

2. RELATED STUDIES

2.1 Point Cloud Classification for Building Rooftop Analysis

The application of point cloud data obtained from advanced technologies such as LiDAR has significantly transformed geospatial analysis (Dawood et al., 2017). This innovative approach has garnered the attention of researchers tapping into these datasets to extract valuable insights about urban landscapes and, more specifically, to evaluate the feasibility of deploying solar panels on building rooftops (Stack & Narine, 2022). A focal point of this effort lies in utilizing point cloud classification techniques, which can discern various objects and surfaces within the three-dimensional environment. By harnessing these techniques, researchers can effectively identify the detailed contours of building structures, ascertain the orientation of roof planes, and anticipate potential obstructive elements (Sun et al., 2016). This approach starkly contrasts traditional two-dimensional methodologies, allowing for a much more exhaustive and nuanced assessment of the diverse attributes associated with rooftops. Consequently, this three-dimensional perspective empowers researchers and planners to make informed decisions regarding optimizing solar panel placements and leveraging rooftops for sustainable energy generation (Stack & Narine, 2022). The fusion of GIS and point cloud data has opened new avenues for geospatial analysis, enabling researchers to analyze urban environments in three-dimensional detail. However, previous studies hardly integrated point clouds and GIS to check the rooftop suitability for solar panel installation.

2.2 Deep Learning and Machine Learning Approaches

The amalgamation of deep learning and machine learning techniques has marked a substantial leap forward in enhancing the precision and effectiveness of point cloud classification (Pal & Hsieh, 2021). Prominent among these methodologies are convolutional neural networks (CNNs) and other sophisticated deep-learning architectures that have showcased exceptional prowess in deciphering intricate roof structures and discerning the diverse array of rooftop attributes (Yang et al., 2023). These methodologies have emerged as dynamic tools capable of automatically extracting valuable information from point cloud data. This encompassing capability spans identifying building footprints, precisely measuring roof areas, and detecting possible shading elements (Pohle-Fröhlich. et al., 2019). The cumulative result of these advancements is a substantially elevated accuracy and depth in evaluating rooftops' suitability for solar panel deployment (Tan et al., 2019). As these methods continue to mature and evolve, their application within the domain of point cloud classification holds tremendous promise for facilitating increasingly refined and reliable analyses, thus paving the way for more informed and effective decision-making processes related to solar energy integration.

3. METHODOLOGY

The methodology adopted in this study is divided into four steps: data acquisition, preprocessing, classification and analysis, and data aggregation. Figure 1 shows a graphical representation of the proposed methodology. This study uses ArcGIS Pro software for GIS-integrated point cloud classification and analysis. Details of each step of the method are explained in the following paragraphs.

3.1 Data acquisition

A UAV-mounted Light Detection and Ranging (LiDAR) device collects the point cloud data. This process begins with mission planning, outlining flight paths and parameters to ensure comprehensive coverage. Laser pulses are emitted toward the ground, and the LiDAR system calculates the return time to determine distances. The collected data generates a point cloud containing detailed 3D coordinates of terrain, buildings, vegetation, and other features. Georeferencing is achieved through GPS and INS for accurate positioning. Collected point clouds are stored in multiple LAS files of manageable sizes. LAS format is an industry-standard file format developed and managed by the American Society for Photogrammetry and Remote Sensing (ASPRS). It is a widely accepted and published standard for exchanging LiDAR data.

3.2 Preprocessing

In the preprocessing step, the point cloud data is in LAS format imported into ArcGIS Pro software, where the "Create LAS Dataset" tool is employed to establish a structured dataset for subsequent analysis. To accurately register the point cloud data with the GIS map, the map data frame should be in the same coordinate system as the LiDAR point cloud tile. The preprocessing involves aligning the coordinate system, performing initial classification, differentiating ground points, and applying quality checks. The dataset is then clipped to focus on the specific study area, and optional filtering and compression steps are used to enhance data quality and efficiency. This processed dataset is the foundation for various geospatial analyses within the ArcGIS Pro environment, including classification, feature extraction, and terrain modeling.

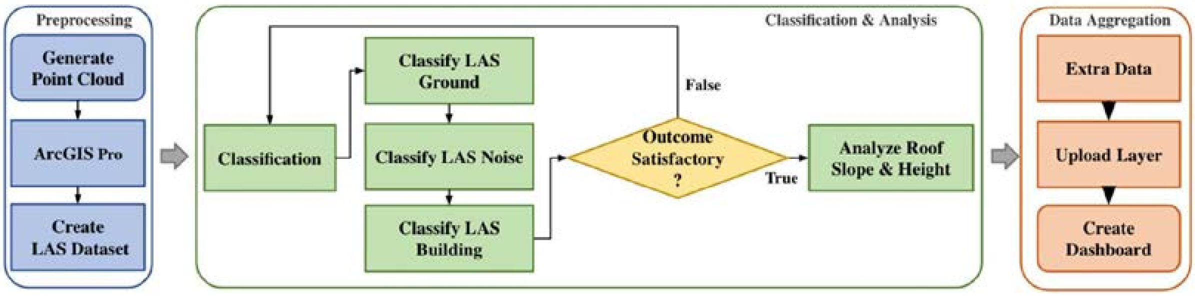

Fig. 1: Overview of the proposed methodology

3.3 Classification and analysis

Once the preprocessing is done, point cloud classification, roof slope analysis, and building height analysis are the next steps. Details of these steps are described below.

3.3.1 Point cloud classification

The point cloud classification is conducted in three steps: (1) using the built-in LAS classification functions such as Classify LAS Ground and Classify LAS Building. (2) 2D shapefile-based classification such as Set LAS Class Codes Using Features, and (3) Classifying a point cloud with deep learning.

First Classify LAS Ground tool is used for the identification of ground points. Ground point assignment is reserved exclusively for LAS points with 0, 1, or 2 class code values. If LAS files employ distinct class code values for unclassified or ground measurements, the Change LAS Class Codes tool can reassign them correspondingly. Next, Classify LAS Building tool is used to classify building rooftops with class code values 0, 1, and 6. Before rooftop classification, LAS data must have classified ground points. This method may not classify points representing walls, vertical facades, and small rooftop features like chimneys. Before building classification, point cloud noises are filtered using Classify LAS Noise function.

The 2D shapefile of buildings is used to enhance the classification quality further. LAS points intersecting the 2D positions of the input polygons are reclassified as buildings. Built-in function Set LAS Class Codes Using Features is used for this purpose. The ArcGIS software uses the American Society for Photogrammetry and Remote Sensing (ASPRS) defined LAS classification scheme. Although this step improves the classification, wall and façade classification is still challenging.

In the final step, a pre-trained deep-learning model, PointCNN, for building classification is used to improve the classification results further. The deep-learning model is inputted as a Deep Learning Package (*.dlpk) in the ArcGIS software. Using the Existing Class Code Handling parameter control over modifications in the target LAS point cloud was achieved. Points already correctly classified (such as grounds) are kept unchanged.

3.3.2 Roof slope and building height analysis

A raster file is created using elevation values stored in the LiDAR points referenced by the LAS dataset for roof slope and building height analysis. Subsequently, a digital elevation model (DEM) of the buildings is created. Next Spatial Analyst function for Slope calculation is used to identify the slope from each cell of the raster file. The Slope tool uses a three-by-three moving window of cells to compute the slope value. The extent of values in the output depends on the measurement units employed. When utilizing degrees, the range of slope values spans from 0 to 90. The analysis can be accelerated using GPU.

Building heights are estimated by comparing the digital surface model (DSM) and the DEM created earlier. The Zonal Statistics tool is used for this purpose. A zone encompasses all regions within the input that share an identical value. The input for defining zones can comprise both raster and feature data types. This tool helps in arithmetic statistics calculations such as Mean, Majority, Maximum, Median, Minimum, Minority, Percentile, Range, Standard deviation, Sum, and Difference. A zonal statistics raster is generated. In this study, the zonal statistics raster represents the building height. Finally, the suitability of the building for rooftop solar panel installation is determined by rule-based checking.

3.4 Data aggregation

During the data aggregation phase, the analysis outcomes, encompassing critical metrics like building heights, mean roof slopes, and evaluations of building suitability, are initially compiled into a structured comma-separated value (.csv) file. This file format aids in organizing the data for seamless processing and interpretation. Subsequently, this collected analytical information is integrated into the university campus's existing Geographic Information System (GIS) shapefile. This incorporation ensures that the analysis outcomes are appropriately aligned with the geographic context of the campus and can be readily accessed for further exploration. Additionally, an additional map layer is generated to enhance the visual representation of these analysis outcomes and promote efficient decision-making. This newly created layer is specifically tailored to present the aggregated results coherently and visually engagingly. The GIS-integrated dashboard within the ArcGIS software serves as a versatile tool for visualizing and interacting with the outcomes, facilitating comprehensive insights and informed actions based on the analysis conducted.

4. RESULTS

The proposed methodology was tested on the expansive 115-hectare main campus of National Taiwan University (NTU) in the Da'an District of Taipei. This sprawling campus hosts a multitude of academic and administrative buildings, exceeding a count of 100. The core objective of this study is to evaluate these buildings' viability for installing rooftop solar panels. To collect the crucial data, an unmanned aerial vehicle (UAV)-mounted LiDAR device was employed, effectively capturing the intricate point cloud representation of the campus. This extensive point cloud dataset was systematically stored in 13 distinct parts, all adhering to the standardized LAS format. Commercial software ArcGIS Pro was used for hosting, processing, and analyzing the point cloud and integrated GIS data. A computer with Intel i7-1370P central processing unit (CPU), 64-gigabyte (GB) random access memory, and 32 GB Intel®Iris®Xe Graphics graphics processing unit (GPU) is used to run the software tool.

In conjunction with this voluminous point cloud dataset, a Geographic Information System (GIS) map showcasing the 2D polygonal representation of campus buildings was prepared. Figure 2 visually depicts the campus's point cloud model and the 2D GIS map. A comprehensive LAS dataset was constructed by amalgamating all 13 LAS files within the ArcGIS Pro software. This amalgamation was executed in accordance with the preprocessing phase described within the methodology. The subsequent phase encompassed applying a three-step classification technique to the compiled LAS dataset, enabling the precise segmentation of building-related point cloud data. The initial stage involved the classification of ground points utilizing the LAS code, following which the 2D GIS polygons facilitated the segmentation of the building point cloud. Eventually, implementing a deep learning model proved instrumental in impeccably classifying and segmenting the points that accurately represented buildings. The outcomes of this segmentation are depicted in Figure 3, which showcases the successful classification outcomes for ground and building points.

Fig. 2: Point cloud (left) and 2D GIS map (right) of NTU main campus

Following the successful classification of building points, a customized DEM raster specific to the campus building was generated. Subsequently, the slope analysis tool was employed to accurately estimate the slope on building rooftops. In this study, the slope measurement unit was defined in degrees, resulting in values spanning the spectrum from 0 to 90 degrees. The ensuing outcome, depicted on the left-hand side of Figure 4, showcases the slope analysis raster. Significantly, the color coding scheme holds informative value: shades of green signify shallower slopes denoting suitability for solar panel installation, while shades of red signify steeper slopes indicating unsuitability. Notably, buildings characterized by substantial rooftop obstructions are prominently indicated in red hues. Furthermore, the color transition observed at building edges is attributed to shifts in slope characteristics, rendering rooftop edges prominently delineated in a striking red color.

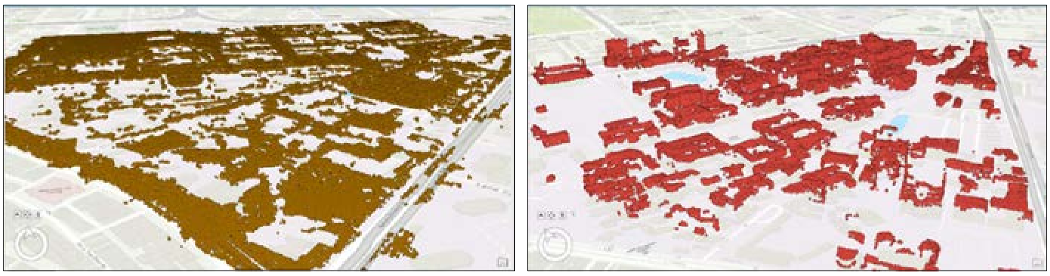

Fig. 3: Point cloud classification results: ground classification (left) and building classification (right)

Building heights were estimated through a comparison between the DSM and DEM rasters, utilizing the Zonal Statistics tool. The outcome of this building height estimation is rendered as a raster, distinguished by color codes corresponding to different heights. This representation is exhibited in the diagram on the right-hand side of Figure 4. Observations indicate that the tool proficiently determined building heights in the majority of cases. However, a few instances (depicted in red) disclosed significant inaccuracies in estimations. Subsequent in-depth analysis established that factors such as noise within the point cloud data, substantial tree obstruction, and inherent point cloud incompleteness substantially influenced the tool's performance.

Finally, the roof slope analysis and building height estimation results were exported into a .csv file, and the existing GIS shapefile was updated. The NTU's GIS dashboard is used to display the analysis results. It can help university administrators to make decisions in a more interactive way. An example of data integration for five buildings is shown in Table 1. The check column of the table shows the suitability of the building for rooftop solar panel installation. The checking result was incomplete for the civil engineering building because of the point cloud incompleteness. The GIS representations of these buildings are shown in Figure 5.

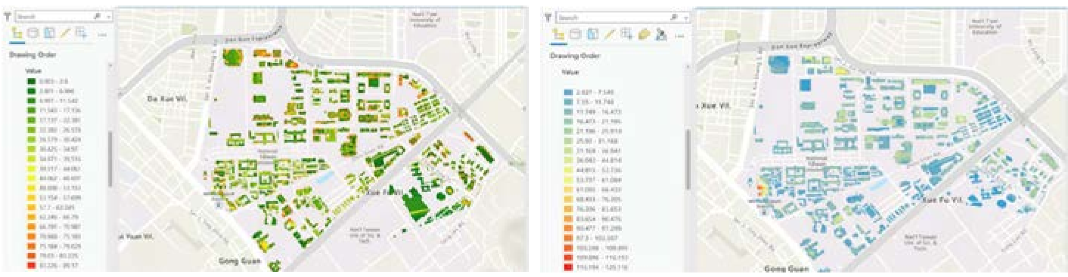

Fig. 4: Results of roof slope analysis (left) and building height estimation (right)

Concluding the process, the roof slope analysis and building height estimation outcomes were transferred into a .csv file, and the pre-existing GIS shapefile was updated concurrently. The integrated results are seamlessly displayed through NTU's GIS dashboard, enhancing the capacity of university administrators to make decisions in an interactive and informed manner. This holistic approach facilitates a more dynamic decision-making process. Exemplifying the integration, Table 1 demonstrates data amalgamation for five specific buildings. Notably, the "Check" column within the table signifies the suitability of each building for rooftop solar panel installation. However, it's essential to underscore that the checking process remained incomplete for the civil engineering building due to inherent point cloud incompleteness. The visual GIS representations of these buildings are depicted in Figure 5. This comprehensive integration emphasizes the analytical and visual richness of the approach.

5. DISCUSSIONS

Although the methodology successfully analyzed building rooftops for solar panel installation, its performance is affected by several factors: point cloud completeness, obstacles from tree leaves, noise in the point cloud data, etc. This method faces a challenge in rooftop analysis of the shorter buildings at the NTU campus because the rooftops of such facilities are often obstruction by tree leaves. Also, the state of these leaves is inherently unstable, subject to growth, pruning, and even shedding, introducing an element of uncertainty into the ongoing analysis. A potential solution could involve implementing filtering criteria during the initial point cloud scanning phase. This strategic approach would enable the retention of essential data points, subsequently alleviating the workload and refining the data for subsequent analysis. Also, the accuracy of the classification methods is subject to several factors, such as the completeness of the existing 2D GIS map data, proper alignment of the map and point cloud data, and the efficiency of the deep-learning model. The incompleteness of the map data and slight discrepancies between map data and point cloud data often leads to manual adjustments.

Table 1: Integration of analysis results in campus GIS map

Building Name	**Area.**	**Mean slope (°)**	**Height (m)**	**Check**
NCREE	13135.83	15.96	21.93	Great
College of Liberal Arts	5980.44	33.23	11.96	Ok
Dept. of Chemistry	11460.91	37.71	27.19	Ok
Floricultural Hall	1381.30	41.26	13.04	Ok
Dept. of Civil Engineering	9686.44	60.05	21.75	Insufficient Data

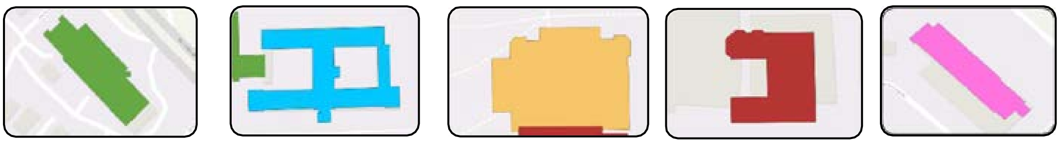

Fig. 5: Building displayed in GIS dashboard. From left: NCREE, College of Liberal Arts, Dept. of Chemistry, Floricultural Hall, Dept. of Civil Engineering

6. CONCLUSION & FUTURE WORK

In conclusion, this study presents a holistic approach to evaluating the suitability of building rooftops for solar panel installation, contributing to the overarching goal of mitigating climate change through renewable energy solutions. The pressing need to curtail greenhouse gas emissions highlights the imperative to transition away from fossil fuels. Integrating renewable sources, particularly solar energy, is pivotal in this attempt. Rooftops provide an underutilized space for solar panel deployment, offering decentralized clean energy generation. However, the effectiveness of such installations hinges on accurate assessments of rooftop attributes. This research introduces a sophisticated methodology amalgamating Geographic Information System (GIS) techniques with advanced point cloud segmentation methodologies. By harnessing airborne LiDAR technology and leveraging deep learning models, the proposed approach deftly addresses challenges such as rooftop slope analysis and building height determination, ensuring the accuracy and applicability of solar panel placement assessments. The study's application on the National Taiwan University campus confirms the practical viability of the methodology.

As universities and organizations worldwide set ambitious carbon neutrality goals, the methods outlined herein provide valuable tools for optimizing renewable energy integration. Moreover, the interdisciplinary nature of this research, encompassing spatial analysis and environmental considerations, exemplifies the multi-faceted approach required to address complex challenges like climate change. We can advance our understanding of sustainable energy practices through such interdisciplinary endeavors and work towards a greener and more resilient future.

7. ACKNOWLEDGEMENT

The author would like to thank the National Science and Technology Council, Taiwan, for supporting this research through research grant No. MOST 109-2221-E-002 -054 -MY3.

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SEMI-AUTOMATIC WORKFLOW FOR AIR-CONDITIONING SYSTEM ZONING AND SIMULATION

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ABSTRACT: *Building information modeling shows its potential in the performance driven design, where multiple design solutions are generated and assessed against certain design goals. This paper proposes a workflow for the air-conditioning system design and simulation on thermal zoning level. Thermal zoning plays a pivotal role in the design thinking of engineers, synthesizing load calculation, equipment sizing, and pipe/duct layout. However, it is often done intuitively with its effectiveness and performance unclear at the outset. To make it quantitative, we decompose the zoning process into two levels (control/system) of space aggregation, joining both semantic and numeric characteristics. For the semantic part, space functions are considered through space labeling, accessibility, and adjacency. Regarding the numeric part, spaces are zoned based on their thermal response similarities, using dynamic mode decomposition of the simulated indoor temperature. A two-level hierarchy of duct/pipe network is generated. It connects spaces within each control zone at the second level, and terminal equipment of each zone at the first level, representing typical fan-coil or variable-air-volume systems. For each zoning scheme, the network and configurations are serialized as Modelica scripts for co-simulation with EnergyPlus. The designer can evaluate different zoning schemes in terms of initial cost, energy consumption, and comfort level, based on the simulation result. The entire workflow is implemented in Grasshopper with self-coded plugins.*

KEYWORDS: *BIM, Thermal zoning, Generative design, HVAC system, Performance simulation.*

1. INTRODUCTION

Building Information Modeling (BIM) provides solutions to the design and management problems in the realm of architecture, engineering and construction, as a platform for data and cooperation. The information can be delivered or retrieved by model view definitions (MVD), BIM query languages, or application programming interfaces (API). However, they barely offer model transformation, which involves the insertion, addition of level of detail, or aggregation of objects (Fischer, 1998). In the forward design process, the model transformation expands the room-based model into another space view for analysis (Suter, 2022), such as energy performance or system design.

Zoning is to transform the room-based model (architectural geometry) to a zone-based model, bridging BIM with building energy modeling (BEM), which is also a critical step in the design of an air-conditioning (AC) system. It is more like an "art" for so many factors to consider, such as space function restriction, space load profiles, convenience for ductwork, balance of performance and cost, and even user preference, both semantic and numeric and hard to quantify. The engineers usually solve the zoning problem intuitively by rule of thumb, leading to one solution. How will it affect the system performance or whether there exists an optimum zoning scheme remains unsolved. Back in 2001, Brahme et al. (2001) investigated the generative ducting based on a grid system at the initial stage. Berquist et al. (2017) continued the idea of generative design and experimentally piloted different zoning on several rooms. Bres et al. (2017) examined the zoning effect of the water heating system for residential buildings, with detailed simulation feedback from TRNSYS. With the lower cost of simulation, it is quite possible to automate the system design and simulation at the zoning phase.

In system design, a thermal zone represents the spaces (part or aggregation of rooms) with heating and cooling requirements that are sufficiently similar so that desired conditions can be maintained throughout using a single sensor (denoted as *control unit*). However, in simulation, the thermal zone stands for the spaces that can be lumped together as a single air node (rephrased as a *simulation unit*), where the parameters of air are uniform. The difference is that the simulation unit is scalable, depending on the modeling target (Fig. 1). For example, it should be in line with the control unit when modeling buildings in operation, as recommended by the ASHRAE Standard. When it comes to the building massing, a shoebox model is enough to study how geometric form affects energy performance. Even one thermal zone for a building is acceptable in city-scale simulation and

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planning. In the system design, the control unit is the smallest on the building scale, which considers the load similarity. When the building gets larger, more system units emerge with load diversity considered. For example, on a system zoning level, equipment can be downsized by staggering the load profiles of control units. A proper zoning and routing of distribution network can reduce the power of fan/pump. More energy distribution can be regulated on a larger scale, such as the exhibition center that has multiple plants or power stations.

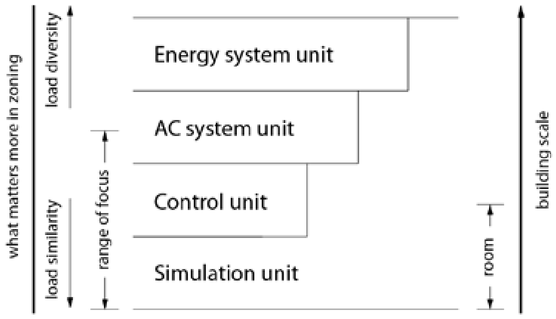

Fig. 1: Different levels of zoning in system design and simulation

Ideally, one should set the control unit exactly the same as the functional space. However, it may have more complex plumbing, ductwork and sensor/equipment installation, increasing the initial cost. There is a trade-off in controlling multiple spaces by a single thermostat since it does cut the cost while causing overheating/cooling. To manifest such an effect, the simulation unit must be smaller than the control unit, or the temperature difference will be evened out during the parameter lumping. Hence, this work takes the functional space as the atomic simulation unit and focuses on the zoning of control unit and system unit.

It is not quite straightforward to evaluate different zoning schemes since it is concerned with the actual system performance and the cost of related equipment configurations. A view model of the distribution network would help with the cost estimation and even the system energy modeling. Bres et al. (2017) pipelined the distribution network generation of the water heating system for residential buildings, by finding the minimum spanning tree (MST) from the potential zone centroids and space boundary vertices. Medjdoub et al. (2018) developed a method for open space fan-coil system layout under specific restrictions. Chen et al. (2022) solved the layout of diffusers and ducts for open spaces with hydraulic balance considered. In related research, the distribution system above the thermal zone level has been rarely visited, especially for non-residential buildings. The problem of distribution network layouts is similar to the design of integrated circuits (Held, 2011) or indoor navigation networks (Fu, 2020).

Following the thread of Bres et al. (2017), this paper details the workflow of thermal zoning and the modeling of air-conditioning distribution systems for office buildings, which can offer multiple zoning schemes in primary design with simulation feedback. After an overview of the methodology, the rest of the paper will be organized into four parts: space view generation, thermal response analysis and zoning, pipe/duct network generation, and model scripting. Each part is exemplified by the same floorplan for reference.

2. METHODOLOGY

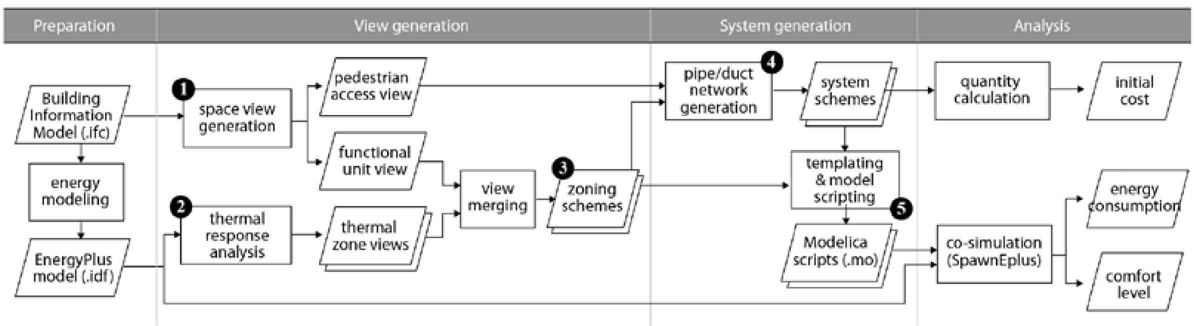

Fig. 2: The semi-automatic workflow of generative thermal zoning toward system simulation

Fig. 2 shows the overall workflow that takes the BIM model (IFC file) as input. In the first preparation stage, the user needs to manually check the integrity of the information model. All spaces must be defined and labeled with their function correctly. All spaces must have boundary components and the 2nd-level boundary defined. To facilitate the testing, templates of construction type, space schedule and load settings are used. The model conversion from BIM to energy model implements IfcOpenShell (Visschers, 2016) and OpenStudio SDK.

The first step includes previous work by Suter et al. (2013), where a method is described to define space views and transform room-based source space data into corresponding space models. Following certain view definitions, the space layout can be selected, aggregated, or decomposed into functional views that are relevant to schematic design (Suter, 2015). The pedestrian space access network is used to identify circulation areas and shafts for plumbing, and the functional unit view for space groups with similarities.

The second step applies Dynamic Mode Decomposition (DMD) (Schmid, 2022) to group spaces with similar thermal responses, similar to the Koopman Analysis application by Georgescu (2015), only more sampler and cost-effective in computation. By tuning the clustering threshold, multiple thermal zone views are generated. The functional unit view and thermal zone views are overlaid as zoning schemes, satisfying both semantic and physical requirements.

The third step implements the potential network that conceptualizes pipe/duct layout in early design, guiding the system distribution network routing. It does not reflect the actual design so the pipe/duct and the equipment may overlay in the schematic diagram. The network first joins spaces of a thermal zone and then connects each zone to the designated shafts. A JSON file collects the geometry and topology of the generated system, with information of peak load, thermostat inherited from zoning schemes.

The fourth step parses the zoning and system into the simulation model. For system simulation, Modelica is used to reflect the control effect across spaces of a thermal zone, which is the temperature bias caused by sharing a thermostat, while EnergyPlus handles the building physics as co-simulation. The workflow is able to reflect the system performance by simulation outputs (energy consumption and comfort level) and quantity takeoffs (equipment, pipe/duct/junction).

Apart from the space view generation (space modeling system, Suter, 2022), the workflow is implemented on the Grasshopper platform with the help of LadybugTools (Roudsari, 2013) and self-coded components. Modularized components make it easier for testing and visualization. The toolkit[1] is written in C# with Rhino core algorithms and CGAL.

3. FUNCTIONAL UNIT VIEW

Although thermal zoning follows clear yet implicit physical requirements, there are more explicit semantic restrictions to it, such as the fire compartmentation forbidding cross ventilation, or the tenant zone for separate energy management. Additionally, designers must consider space functions to avoid serving bathrooms and offices with the same duct system. The functional unit view can depict such a function isolation.

In previous work (Suter, 2022), a data processing pipeline was proposed for defining space views using space ontologies and layout transformation operations. The generated space view model can help with the space layout analysis by offering insights int space function, accessibility, orientation, daylighting or ventilation. In the first step, room-based source data are extracted from BIM by IFC class filters, such as space geometry and related objects. The second step transforms the data to a source space layout, where spaces are labeled automatically or manually. Labels are assigned by default according to the IFC to space ontologies class mapping. Additional labels are inferred by semantic reasoning. In the third step, the source space layout is transformed into a certain space view, by its defined operation sequence (including filtering, selection, aggregation and update).

The functional unit view uses the space access network to identify the cluster in terms of adjacency and function. The space access network originates from a spatial relation network that builds upon centroid nodes of all layout elements (e.g., spaces and doors), with their spatial relations as edges. Such relations include containment, adjacency, proximity, and partial enclosure. A door adjacent to two spaces indicates an accessible path lies in between, while the isolated node with no accessibility proves to be a shaft. Different levels of depth in the space access network tell how important a space functions as a circulation area. Typically, the main circulation space contains the elements accessing each functional unit, which form a node cut-set that partitions a space access network into multiple components. Spaces are then merged as a functional unit with classification (function label) inferred from the spaces within.

[1] https://www.github.com/ian-quinn/tellinclam

Fig. 3 Sample floorplan [2]

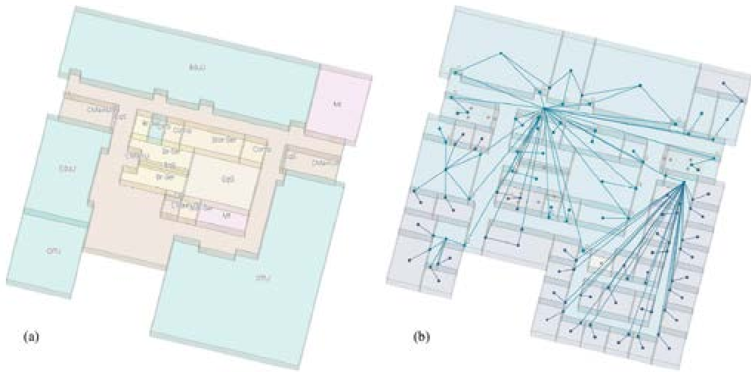

Fig. 4 Generated view of (a) functional unit (b) space access network

Fig. 3 displays the floorplan used for this work, labeled with detail functions. In the example (Fig. 4-a), there are seven major functional units: two marked as educational units (EduU) that include classrooms and affiliated spaces; two marked as office units (OffU) according to their major function; two meeting units (Mt); one circulation unit including the main corridor, stairs and atrium. This view will act as an overlay to the thermal zoning, reflecting function restrictions.

4. THERMAL ZONING VIEW

The control needs for air-conditioning are directly reflected by the thermal responses of all spaces. Taking the whole floorplan as one dynamic system, each space may have different characteristics. The essence of thermal zoning is to apply the same control logic to several spaces sharing similar dynamic characteristics, thus achieving an acceptable control effect with less controller and actuator.

Although many factors are intertwined in this complex dynamic system, such as operation schedule, internal loads, solar radiation, thermal resistance and thermal mass of structure components, the indoor float temperature is one direct externalization of such dynamics. By measuring the time series of temperature waves, we may identify the dynamic characteristics of each space, and aggregate them as thermal zones based on their similarity. Inspired by Georgescu (2015), Dynamic Mode Decomposition (DMD) is used to perform the Koopman Analysis, extracting the dominant modes and their properties based on the free-float temperature data.

The general idea of the Koopman Analysis is to study the time evolution of observables under iteration of a nonlinear system through the Koopman operator U, which is linear but infinite dimensional (Raak, 2016). Considering a dynamic system $\boldsymbol{x}_{k+1} = \boldsymbol{f}(\boldsymbol{x}_k)$ evolving on a manifold M, $\boldsymbol{f}$ is a non-linear map describing how $\boldsymbol{x}$ evolves in discrete time. The operator U acts on the scalar function $g: M \to \mathbb{R}$ (1), which is the selected observable (or the system output), then describes its evolution in a linear, infinite space, along with the system $\boldsymbol{f}$:

$$Ug := g \circ \boldsymbol{f} \qquad \mathrm{Ug}(\boldsymbol{x}_k) = \mathrm{g}\big(\boldsymbol{f}(\boldsymbol{x}_k)\big) = \mathrm{g}(\boldsymbol{x}_{k+1}) \tag{1}$$

Given eigen-decomposition of U (2), we may generally express the vector function $\boldsymbol{g}: M \to \mathbb{R}^n$, in terms of Koopman eigenfunctions ϕ_j and eigenvalues λ_j by (3),

$$U\phi_j(\boldsymbol{x}) = \lambda_j \phi_j(\boldsymbol{x}), \quad j = 1, 2 \ldots \infty \tag{2}$$

$$\boldsymbol{g}(\boldsymbol{x}) = \sum_{j=1}^{\infty} \phi_j(\boldsymbol{x})\boldsymbol{v}_j \qquad \boldsymbol{g}(\boldsymbol{x}_k) = \sum_{j=1}^{\infty} \lambda_j^k \phi_j(\boldsymbol{x}_0)\boldsymbol{v}_j \tag{3}$$

where $\{\boldsymbol{v}_j\}$ is a set of vector coefficients called Koopman modes of map $\boldsymbol{f}$. The set of eigenvalues $\{\lambda_j\}$ indicates the growth rate and frequency of each mode. The practical idea behind this is to collect a set of data, identify observable $\boldsymbol{g}$ of interest, and then express it in terms of Koopman modes and eigenvalues (Chen, 2012). For example, one may take the time series temperature of spaces as observables (data snapshots $\mathbf{X}(\mathrm{n} \times \mathrm{m})$), and analyze the thermal responses of the complex system by eigenvalues and modes.

[2] https://www.angelo.edu/live/news/12569-no-place-like-home

The DMD algorithm approximates the modes and eigenvalues by a finite data set, with a variant of the Arnoldi method described in Chen et al. (2012) and summarized as (Alg. 1). Assuming the dynamic $\boldsymbol{f}$ is linear with $\boldsymbol{f}(\boldsymbol{x}) = \boldsymbol{A}\boldsymbol{x}$, then eigenvalues of $\boldsymbol{A}$ are also eigenvalues of U. Furthermore, if $\boldsymbol{g}(\boldsymbol{x}) = \boldsymbol{x}$, then modes $\boldsymbol{v}_j$ are the corresponding eigenvectors of $\boldsymbol{A}$ (Rowley et al., 2009). However, eigen-decomposition of A is hard to solve directly due to its large dimensions. Alg. 1 further approximates A by projecting it onto one Krylov subspace $\mathcal{K}$ expanded by $\boldsymbol{K}$, then calculating the eigenvalues and eigenvectors with the low-rank operator. Note that in real-world non-linear problems, there must be a bias $\boldsymbol{r}$ representing $\boldsymbol{x}_m$ within $\mathcal{K}$, it is critical to find suitable constant vector(s) $\boldsymbol{c}$ to minimize $\boldsymbol{r}$ in least-square sense (Alg. 1 Line 2). Then, $\boldsymbol{C}$ is regarded as an approximation of the action of the Koopman operator on the associated finite dimensional space $\mathcal{K}$ (Raak, 2016). The resulting empirical Ritz values and vectors (Alg. 1 Lines 7, 8) behave in precisely the same manner as the eigenvalues and modes v of U (1). The theoretical deduction can be found in Rowley et al. (2009).

Algorithm 1 DMD (one variant of standard Arnoldi)

Input snapshots of observable $[\boldsymbol{x}_0\ \boldsymbol{x}_1 \cdots\ \boldsymbol{x}_m]$, $\boldsymbol{x}_k \in \mathbb{R}^n$

Output Ritz values $\{\lambda_i\}$, Ritz vectors $\{\boldsymbol{v}_i\}$

1: $\boldsymbol{K} := [\boldsymbol{x}_0\ \cdots\ \boldsymbol{x}_{m-1}]$, $\boldsymbol{c} := [c_0\ \ldots\ c_{m-1}]^T$

2: $\boldsymbol{x}_m = \boldsymbol{K}\boldsymbol{c} + \boldsymbol{r}$, $\quad \boldsymbol{r} \perp span(\boldsymbol{x}_0 \ldots \boldsymbol{x}_{m-1})$ ▷ find constant $\boldsymbol{c}$ to construct $\boldsymbol{x}_m$ with minimal residual in least-square sense

3: $\boldsymbol{c} = \boldsymbol{K}^{+}\boldsymbol{x}_m$ ▷ one solution by observation

4: $\boldsymbol{K}^{+} = (\boldsymbol{K}^{*}\boldsymbol{K})^{-1}\boldsymbol{K}^{*}$ ▷ when $\boldsymbol{K}$ is not full rank

5: Construct the companion matrix

$$\boldsymbol{C} := \begin{bmatrix} 0 & 0 & \cdots & 0 & c_0 \\ 1 & 0 & & 0 & c_1 \\ 0 & 1 & & 0 & c_2 \\ \vdots & & \ddots & & \vdots \\ 0 & 0 & \cdots & 1 & c_{m-1} \end{bmatrix}$$

6: $\boldsymbol{C} = \boldsymbol{T}^{-1}\boldsymbol{\Lambda}\boldsymbol{T}$ ▷ one possible decomposition

7: Output diagonal $\boldsymbol{\Lambda}$ as Ritz values $\{\lambda_1, \ldots, \lambda_m\}$

8: Output $\boldsymbol{V} := \boldsymbol{K}\boldsymbol{T}^{-1}$ as Ritz vectors $\{\boldsymbol{v}_1, \ldots, \boldsymbol{v}_m\}$

There are various approximation methods of $\boldsymbol{A}$ span over the algorithm spectrum, from Koopman analysis (accurate, complex) to DMD (coarse, simple). For example, one can implement a classical Arnoldi algorithm, or by other variants like QR decomposition, SVD decomposition (standard DMD), or Proney-type method (Hankel DMD) (Schmid, 2022). Alg. 1 applies a variant Arnoldi method that takes $\boldsymbol{c} = \boldsymbol{K}^{+}\boldsymbol{x}_m$ as one solution for Line 2 by observation. It is not unique and the result needs cross-verification.

By simulation, a typical school building may yield year-long (8760 hours) time-series data on the free-float temperature, of hundreds of spaces. The space dimension of each snapshot is far less than its time dimension (n ≪ m), where rank deficiency is inevitable. The standard DMD method performs poorly because its SVD process truncates the matrix to n×n with lots of information loss on the time dimension. While, the Arnoldi method gives nice accuracy because it expands the matrix to m×m without truncation. A similar method is applied to the air temperature analysis of a conditioned room (Boskic, 2020), with the data dimension 28×241, and a power system whose data dimension is 7×24~120 (Raak, 2016).

In order to get the free-float temperature and perform the analysis, the following workflow is implemented based on the Grasshopper platform. It includes three steps: 1) build up the energy model by retrieving IFC information; 2) implement the Arnoldi algorithm on the temperature series output by simulation; 3) perform hierarchical clustering and output multiple thermal zoning schemes.

The building floorplan can be manually drawn or transplanted from IFC by IfcOpenShell (Visschers, 2016). The LadybugTools (Roudsary, 2013) helps with the energy modeling based on the geometry and function labeling, by calling OpenStudio SDK. EnergyPlus 9.6.0 performs the year-long simulation without any system, using construction and space function templates from ASHRAE Standard 189.1-200. Because EnergyPlus 9.6.0 does not support thermal zones with multiply-connected region, some corridors are further divided in this case.

Fed with the temperature series, Alg. 1 yields the empirical Ritz vectors and values approximating the Koopman modes $\boldsymbol{v}$ and their eigenvalues λ. If the complex number λ falls near the unit circle, it represents a more steadily evolving mode. Here we name the Growth as $|\lambda|$, the Norm as $|\mathbf{v}|$, and the Frequency as $Im(log(\lambda))/2\pi\Delta t$. Δt stands for the sampling period which, in this case, is 1 hour.

The dominant modes must be selected and cross-validated because the Arnoldi method generates tons of modes (equal to the number of time dimensions). A simple way is to identify the energy-intense frequency bands, then rank all modes by their growth value in descending order, and look up for those modes with the largest norm. In this case, by Discrete Fourier Analysis, the frequency bands of 1/8760, 1/24, and 1/168 take up over 95% energy of the entire system, which corresponds to the year, day and week period, in line with the actual operation schedule. In this way, the dominant modes are highlighted in red in Table 1.

Table 1: Modes ranked by growth

mode	growth	norm	1/frequency
8237	1.000038	9.185662	9656.458
8238	1.000038	13.93669	-9656.458
8418	1.000029	51.34232	168.4023
8419	1.000029	64.30705	-168.4023
5799	**1.000026**	**249.9451**	**23.92526**
5800	1.000026	267.1617	-23.92526
8239	0.999999	82.70703	∞
5845	0.999960	261.9814	24.0553
5846	0.999960	303.0435	-24.0553
5779	0.999950	150.2885	23.9970

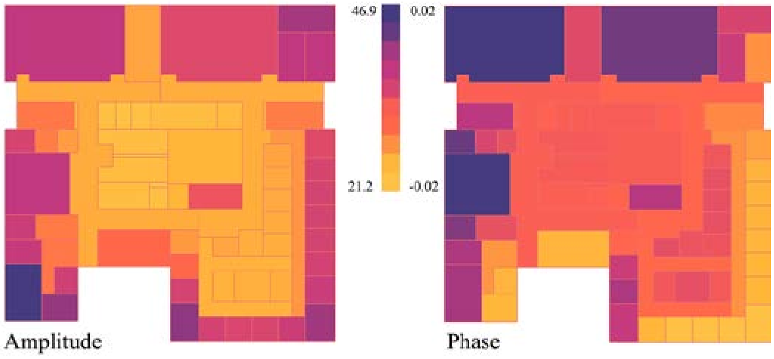

Fig. 6 The distribution of amplitude and phase of mode 5799.

Within the dominant mode, each complex number in $\boldsymbol{v}$ represents the dynamic characteristics of a space. In Fig. 6, each space is rendered by pseudo color based on the calculated amplitude (norm) and argument value as follows. Space aggregation can be identified visually.

$$Amp = \sqrt{Re(\boldsymbol{v}_i)^2 + Im(\boldsymbol{v}_i)^2}, \quad Arg = \arctan\left(\frac{Im(\boldsymbol{v}_i)}{Re(\boldsymbol{v}_i)}\right)$$

To make it quantified, the hierarchical clustering is implemented on the 2-dimensional data space by their Euclidian distance. The hierarchical clustering gradually increases the threshold of cluster distance (e.g., the similarity of dynamic response), and generates multiple layouts (Fig. 7) as the generative zoning process.

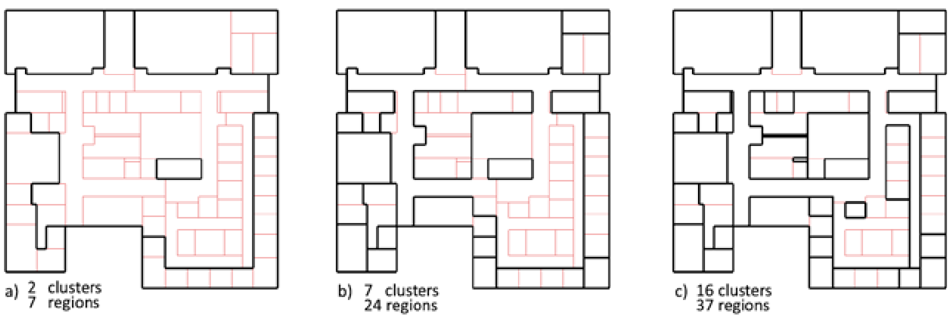

Fig. 7: Different thermal zoning schemes based on different cluster distance.

The final zoning scheme is the overlay of the thermal zoning view and the functional unit view, with all unconditioned spaces ignored. Spaces already grouped in thermal zoning may be partitioned again by the functional unit view.

5. PIPE/DUCT NETWORK VIEW

To better evaluate the effectiveness of zoning schemes, a detailed pipe/duct network view for the distribution system is needed. The designer may grasp a basic idea of system layout and initial cost through the view, even the performance of comfort control and energy consumption via automatic simulation. Similar to the space access network, a pipe/duct network is introduced to describe the path how cooling/heating energy is delivered to each space. Since the zoning process focuses on space aggregation, the terminal ductwork within each space remains unaltered and is consequently not taken into account.

Bres (2017) devised a loop pattern for the water heating system generation, connecting radiators of each zone with pipes around the floorplan perimeter. Due to the buoyancy effect, the radiators are normally located at the baseboard so the water loop should avoid the circulation area. On the contrary, the air-conditioning system incorporates sizable equipment and ducts, making it more cost-effective to distribute cool/warm air through the ceiling void, from core to perimeter. With such a tree pattern, the pipe/duct network starts from core shafts or mechanical rooms and then spreads outward via circulation areas to terminal spaces.

Pipe and duct require dedicated space. Typically, the ceiling void in circulation areas is allocated for the installation of electric wiring, ductwork or plumbing. These circulation areas can be identified based on the space access graph in section 3 (Fig. 4-b). In graph theory, the degree of a node denotes the number of edges incident to that node. Thus, the inaccessible shafts have a degree of zero while the corridor usually has the largest degree. Other spaces (degree > 2), such as waiting rooms, may serve as circulation areas in their own functional unit. The space view in Fig. 8 can be drawn following the methods in section 3.

Algorithm 2 Generate Skeletons

Input rooms as polygon set $R = \{P_0, P_1, \ldots, P_n\}$. Within set P_0 represents the outer boundary while others inner holes. η_{min}, η_{max}
Output list of edge set $list\{S\}$

```
Merge any two set R1 and R2 if R1[0] and R2[0] overlap, then replace R1[0] and R2[0] by the polygon of their Boolean union.
Initiate list{S}
for each remaining R do
    Solve Straight Skeleton by R, build graph G(V, E) from generated inner bisectors, output other bisectors as edge set B
    d ← 0
    for each v in V do
        time(v) ← "time" value of the vertex
        degree(v) ← the degree of vertex
        if degree(v) = 1 then
            if time(v) < η_min then
                remove v from V
            else
                Find edges e1, e2 incident to v from B, then add their bisector as edge to G
            if time(v) > d and time(v) < η_max then
                d ← time(v)
    Get offset polygon set C by Straight Skeleton algorithm from R by inward depth of d
    Break up all edges in S by intersection points with C
    Remove edges from S that are inside the region formed by C
    Merge edges in C with S, then append S to list{S}
```

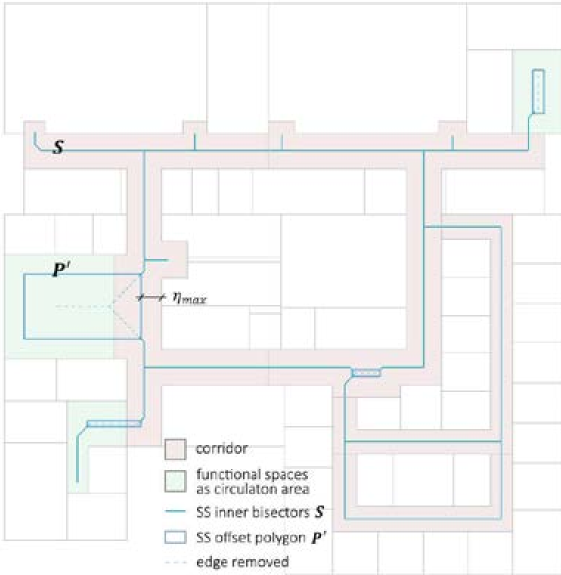

Fig. 8: Circulation areas and the prototype network

Upon the Boolean union of circulation areas, Alg. 2 generates the prototype of potential network by the Straight Skeleton (SS) algorithm. The straight skeleton is defined by continuously moving the polygon edges inwards parallel to themselves at a constant speed. Edges may split in two (split event) or vanish (edge event) due to vertices collision. During this offset process, a set of lines will be traced out by the moving vertices, which is the straight skeleton. It represents the shape well by centerlines, making it suitable for guiding the installation of ductwork. However, for open space such as foyer, the pipe/duct usually walks along the wall (not across the space), which means the offset process should stop at a certain depth. To achieve this, Alg. 2 takes a two-step skeleton generation. Firstly, generate the straight skeleton from the boundary polygon $\boldsymbol{P}$ (Sugihara, 2013), and filter out all interior bisectors as a set $\boldsymbol{S}$. Each vertex in it has a "time" attribute that marks how long it walks during the offset process. Secondly, generate the offset polygon $\boldsymbol{P'}$ by the largest "time" value below the threshold η_{max} (3m, for instance). Thirdly, perform a Boolean subtraction on $\boldsymbol{S}$ using $\boldsymbol{P'}$, and then merge it with $\boldsymbol{P'}$ as the final prototype $\boldsymbol{S}$ (Fig. 8). $2 \times \eta_{max}$ represents the typical width that distinguishes a corridor from a hallway.

In terms of the actual pipe/duct layout, the resulting set of line segments has too many joints, twists and branches. They need further simplification by extension, pruning and alignment. For extension, a vertex generated in an 'edge event' needs to be connected to the mid-point of the edge from which it is collapsed (Fig. 9-b). For pruning, a vertex with too small "time" value below the threshold η_{min} (1m, for instance), as well as the edge incident to it, needs to be pruned (Fig. 9-c). $2 \times \eta_{min}$ represents the minimum width of a typical corridor. Such redundant "branches" are often caused by zig-zag polygon boundaries. For alignment: 1) Considering all prevalent edge directions (edges below length threshold d are ignored), edges in $\boldsymbol{S}$ are grouped by Quality Threshold (QT) clustering with threshold d. The QT clustering takes the maximum cluster diameter as input, finding clusters with guaranteed quality. 2) In each group, an edge can be the alignment baseline only if the total swept area by projecting others to it reaches the minimum. If multiple candidates exist, pick the median. The axis is a line segment that connects all projected vertices along that baseline. 3) The axis will pull the nearby vertices (within the range of d) onto itself while keeping their edge connections. The alignment process aims for the most simplified $\boldsymbol{S}$, by iteratively increasing d until $\boldsymbol{S}$ intersects with any space boundary.

Algorithm 3 Align Skeletons

Input distance threshold d, angle threshold θ, set of edges S
Output set of aligned edges

Initiate $list\langle axis\rangle$
Divide S by Quality Threshold clustering into $\{S_0, \dots, S_n\}$, taking parameter d and θ measuring the distance and angle between two edges. Edges with length smaller than d are ignored.
for each S' in $\{S_0, \dots, S_n\}$ **do**
  $box \leftarrow$ outward offset polygon by d
  Group edges if their box overlap, resulting $\{S'_0, \dots, S'_n\}$
  for each S'' in $\{S'_0, \dots, S'_n\}$ **do**
    $area_{min} \leftarrow \infty$
    $axis \leftarrow S''[0]$
    for each edge e_i in S'' **do**
      $area \leftarrow 0$
      initiate $list\langle point\rangle$
      for each edge e_j in S'' except for e_i **do**
        $area \leftarrow area+$the area of region swept by e_j projected to e_i
        append projected endpoints to $list\langle point\rangle$
      if $area < area_{min}$ **then**
        $area_{min} \leftarrow area$
        $axis \leftarrow$ new edge spanning all points in $list\langle point\rangle$
    Append $axis$ to $list\langle axis\rangle$
Build graph $\mathbf{G}(V, E)$ from S
for each edge $axis$ in $list\langle axis\rangle$ **do**
  for each vertex $\mathbf{v}$ in $\mathbf{G}(V, E)$ **do**
    if distance between $\mathbf{v}$ and $axis < d$ **then**
      Project $\mathbf{v}$ to $axis$
Output E

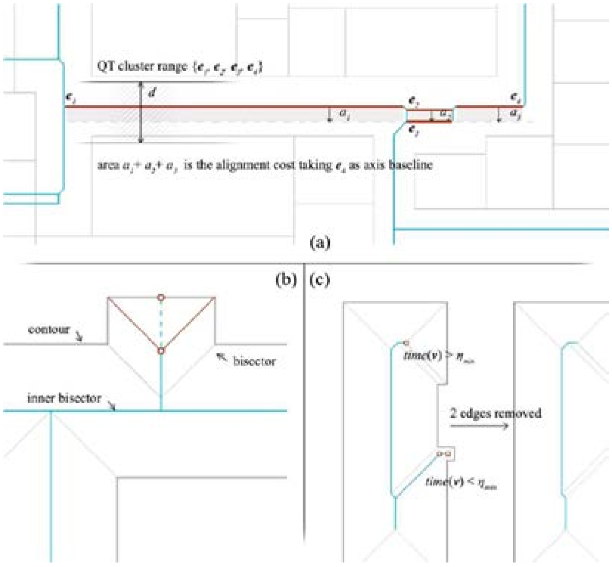

Fig. 9: (a) edge alignment on QT clustering. (b) extrusion of inner bisector with 1-degree vertex. (c) remove vertices with too small "time" value.

In this work, the door locations serve as the entry points to wire in the main network to each space. Such information can be retrieved from BIM (either by IFC or gbXML). If not available (such as a shaft or part of an open space), the centroid of the space region will be used instead. The algorithm finds the Manhattan path between the entry point and the main network by the minimum cost, and then adds them to $\boldsymbol{S}$. Additional penalties will be counted if the path collides with space boundaries. The line segment set $\boldsymbol{S}$ forms a graph $\boldsymbol{G}(V, E)$, serving as the potential network for the detailed layout of pipe/duct system.

According to the hierarchy of zoning outlined in section 1, the terminal nodes (functional spaces) within a thermal zone are connected to a distribution node, representing a variable-air-volume box or air handling unit (AHU). Subsequently, all distribution nodes are connected to the source nodes (shaft or mech rooms). All routes follow the potential network given by an undirected, weighted graph $\boldsymbol{G}(V, E)$. The 2nd-level connection is a Steiner tree problem on terminal nodes $N \subseteq V$ with Steiner points provided as $V \setminus N$. The 1st-level connection can be regarded as the Shortest Path Tree that grows from one source node to all distribution nodes.

Algorithm 4 Get Steiner tree of subset vertices from a graph

Input undirected, weighted graph $\mathbf{G}$, terminal vertices set N
Output Steiner tree graph T

Create the sub graph $\mathbf{H}(V, E)$ by Floyd-Warshall algorithm, making $V \supseteq N$ and E contains all possible path between any $v \in N$
Initiate set V_{del}
Initiate adjacency matrix $A[i, j] \leftarrow e(v_i, v_j),\ i, j \in |V|$
Initiate adjacency matrix $a[i, j] \leftarrow weight(e(v_i, v_j))$
for k from 1 to $|V|$ **do**
  if $degree(v_k) = 2$ **then**
    $v_i, v_j \leftarrow$ neighbours of v_k
    $A[i, j] \leftarrow A[k, i] \cup A[k, j]$, then $A[k, i], A[k, j] \leftarrow \emptyset$
    $a[i, j] \leftarrow a[k, i] + a[k, j]$, then $a[k, i], a[k, j] \leftarrow 0$
    Append v_k to V_{del}
Generate minimum spanning tree $T(V', E')$by Kruskal algorithm based on adjacency matrix $a[i, j]$
for each $e(v_i, v_j)$ in E' **do**
  $e(v_i, v_j) \leftarrow A[i, j]$ ▷ map edges back to H
$V' \leftarrow V' \cup V_{del}$ ▷ bring back relay vertices
Simplify T then output

Algorithm 5 Find centroid of tree

Input undirected, weighted tree graph $\mathbf{T}(V, E)$
Output directed, weighted tree T'

Start form any $v_x \in V$, find the furthest vertex v_0 by Dijkstra algorithm
Start from v_0, find the furthest directed $path = \{v_0, \dots, v_n\}$ by the same Dijkstra algorithm
Locate the middle point v_m on $path$ by length
$V \cup \{v_m\}$, $E \cup \{(v_{m-1}, v_m), (v_m, v_{m+1})\}$
Traverse T from v_m down to leaf node to build the tree T'

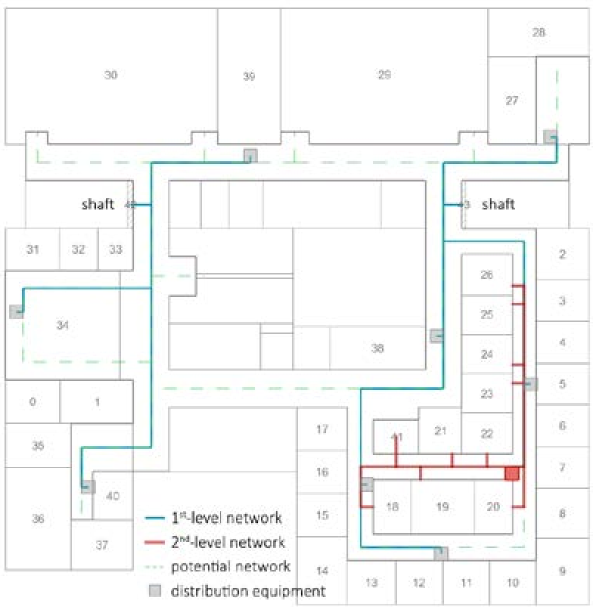

Fig. 10: A sample duct/pipe generation based on the potential network

Alg. 4 describes the steps for solving the 2nd-level connection within a zone: 1) Create the sub-graph $\boldsymbol{H}$ based on $\boldsymbol{G}$, containing the terminals in set N and their possible paths by modified Floyd–Warshall algorithm. 2) Map the graph $\boldsymbol{H}$ to $\boldsymbol{H'}$ by removing relay nodes (degree = 2). 3) Find the MST joining all nodes in the graph $\boldsymbol{H'}$ by Kruskal algorithm, then map it back to $\boldsymbol{H}$. The resulting graph $\boldsymbol{T}$ is the Steiner tree that connects all terminals. To locate the terminal equipment that handles the zone air, Alg. 5 first finds the longest path $\boldsymbol{P}$ by running the Dijkstra furthest path algorithm twice from any node, then adds the mid-point of $\boldsymbol{P}$ as the root node of $\boldsymbol{T}$. The root node minimizes the average path to leaf nodes, implying the minimal cost of distributing cooling/heating air to each space.

All distribution nodes are connected to the source nodes (shaft or mechanical room) along the potential network $\boldsymbol{G}$, in the 1st-level connection. They are clustered by the shortest walk to the nearest source candidate, then get connected by a shortest path tree rooted in that source node (Alg. 4, with Kruskal-MST replaced by Dijkstra shortest-path-tree). It is an edge-weighted breadth-first search that traverses a tree down to every leaf with the same speed.

For simplification, the graph $\boldsymbol{G}$ takes the length of each duct/pipe segment as edge weight. The pressure loss is roughly proportional to the length according to the Darcy-Weisbach equation. Especially in the low-speed ductwork design, a constant pressure loss per unit of duct length is commonly assumed. Moreover, the algorithm ignores many geometric constraints, such as the collision of equipment and ducts in the ceiling void, or the oversized duct that cannot fit in the shaft. Since the generative zoning focuses more on space/system topology than the construction document, it is omitted for our current work.

6. MODEL SCRIPTING

To evaluate the initial cost, energy consumption, and the control effectiveness of zoning schemes at the space level, the co-simulation binding Modelica and EnergyPlus is an ideal choice. *Spawn* (of EnergyPlus) is the latest whole-building energy simulation engine developed by the U.S. Department of Energy, National Labs and industry. It reuses the envelope and daylighting modules of EnergyPlus and couples them with the AC system and control modules from Modelica Buildings Library (Wetter, 2020). This division of tasks optimally leverages EnergyPlus for efficiently solving multi-zone building physics–a task can be time-consuming for Modelica. And, because EnergyPlus takes thermal zone as the basic simulation unit, Modelica is needed for inspecting different behaviors of spaces within a thermal zone.

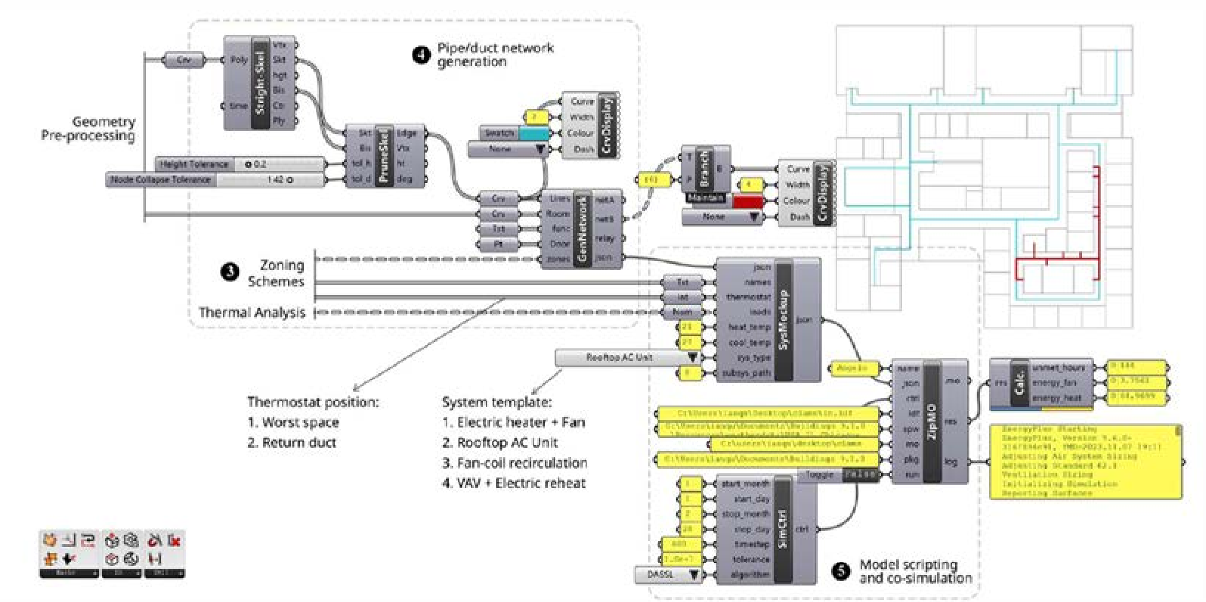

Fig. 11. Workflow of model scripting in developed Grasshopper components.

Based on the typical-day load results from EnergyPlus, the nominal airflow rate is calculated for each space. Then, the algorithm does the equipment and ductwork sizing to meet the nominal airflow. It applies the Equal Friction method to decide the diameter and the pressure loss, which mimics the decision process of engineers.

Following the algorithms in section 2.4, the two-level distribution network, accompanied the functional spaces, is first serialized in a JSON file (component GenNetwork in Fig. 11). Then, joined with the system and simulation configuration, the JSON is further parsed into the Modelica scripts. The user may customize different systems and control templates in the component SysMockup. When component ZipMO is toggled on, the program will call OpenModelica Shell to perform the simulation and analyze the result.

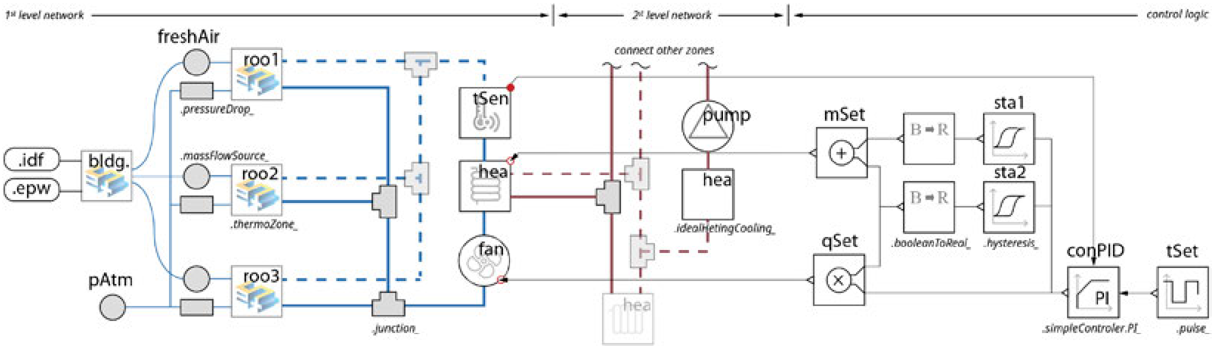

Fig. 12. A sample connection of Modelica model

Fig. 12 gives an example of the generated Modelica model, demonstrated by a recirculation fan-coil system with the water heater and two-speed fan. Each 'thermalZone' component represents a functional space (altogether 43 conditioned spaces), with specific air leakage and fresh air ventilation rate. It exchanges temperature data with the corresponding zone in the EnergyPlus by *Spawn*. The PI controller takes the temperature as input from the sensor mounted on the return duct, and controls the indoor temperature around 21°C during working hours (9:00~18:00). Above the control zone level, a water loop connects all terminal equipment. The fan/pump and heat exchanger are ideal models to give rough estimations. They can be replaced with actual models given detailed parameters, such as performance curves.

Table 2: Simulation results of sample cases

Schemes	Uncomfortable hour (h)	Unmet hour (h)	Fan Power (kWh)	Heat (kWh)	Duct area (m^2)	Pipe length (m)	AHU	Model Equations	Simulation Time (s)
Fig. 4	726	1050	30.82	3317.04	53.60	34.38	9	16857	212
Fig. 7 (a)	1294	1970	35.66	3298.66	78.33	17.54	8	16662	249
Fig. 7 (b)	122	298	33.47	3349.66	24.38	42.67	22	19392	349
Fig. 7 (c)	101	276	34.38	3349.10	17.61	50.75	26	20172	277

The workflow has been tested against 4 zoning schemes for 14 winter days in Chicago. There is a clear trend in Table 2 that the unmet hour decreases along with the increase of control zones. Normally, a control bias of ±1°C is acceptable for comfort conditioning. Hence, the unmet hour accumulates the working hours where the temperature is outside the range of 20~22°C. Similarly, the uncomfortable hour is calculated for temperatures outside the comfort range (20~25°C). In the last case, Fig. 7 (c), 101 uncomfortable hours indicate that one space may get unconditioned for 10 minutes a day on average. However, if 19°C is acceptable, the uncomfortable hour will be zero. Given proper equipment costing spreadsheet, this workflow can offer insights into the advantages and disadvantages of different zoning schemes, in terms of comfort level, initial cost and future energy bills. Such information can facilitate the decision-making process.

7. DISCUSSIONS

This paper introduces a semi-automatic workflow for thermal zoning, the AC distribution system generation, and model scripting. Such a workflow can assist engineers in exploring various zoning schemes and system layouts, taking a step forward toward the generative design driven by simulation. Additionally, it incorporates two unique views into the space view model. One is the thermal response view of spaces (Fig. 6), enabling designers to quickly zone the spaces by color similarity. The other is the potential distribution network view (Fig. 10) that outlines the cost of delivering energy to terminal spaces. However, there are several topics not addressed in this paper, left for future work:

1) The space ontology needs to be enriched, to describe more space relations such as the tenant zone and fire compartmentation. Different tenants must be considered during thermal zoning because their energy

consumption is metered separately. Also, ductwork can be a fire hazard for spreading heat between two compartments.

2) The algorithm for the 1st-level network can be improved, to consider the capacity of terminal equipment and the hydronic balance. It is preferable to evenly distribute the cooling/heating load of zones across multiple risers, ideally making the riser the root node that a tree grows from. If there are outlying spaces in the floorplan with unique load profiles, the algorithm is better to isolate them as distinct system zones (with a direct expansion system for example).

3) More system and control templates are required, for a wide range of system performance comparisons. To a certain degree, the current 2-level network has some universality. Without the 1st-level network, it can be the ductwork of rooftop packaged units. With 1st-level modeled as water pipes and 2nd-level as air ducts, different proportions of water and air can resemble systems from fan-coil (less or no duct) to AHU (more duct). When modeled as air ducts, it suits the constant or variable air-volume system. Each system has specific configurations for model scripting, such as 2-pipe/4-pipe fan-coil, VAV-box reheat, or outdoor air duct.

4) The algorithm lacks the ability to evenly lay out the diffusers and ductwork in an open space. Nevertheless, when the open space has specific function zones allocated, it resembles a multi-room floorplan, with physical partitions replaced by air walls. Under that condition, the pipeline still works given a proper assumption of the airflow rate between spaces (for EnergyPlus modeling in thermal analysis and co-simulation).

8. ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support from China Scholarship Council in conducting the project.

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GOING BEYOND ENERGY CONSUMPTION: DIGITAL TWINS FOR ACHIEVING SOCIO-ECOLOGICAL SUSTAINABILITY IN THE BUILT ENVIRONMENT

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ABSTRACT: *Digital twins have attracted much of the attention from the researchers and policy makers as a potent industry-agnostic concept to support ambitious decarbonization goals. Consequently, much of the latest research has focused on computational methods for building and connecting digital twins to monitor and measure energy consumption and resulting emissions from buildings. At the same time, it has been recognized that achieving a truly sustainable built environment goes beyond environmental sustainability and is much more complex, calling for approaches that transcend any single discipline. Initiatives such as the National Digital Twin in the UK and globally, begin to offer a long-term vision of interconnected, purpose-driven and outcome-focused digital twins, grounded in systems thinking. Such approaches recognize the economic, social and ecological layers as critical data components in these digital ecosystems for understanding the built environment as a whole. Yet, social and ecological sustainability will remain difficult to address without involving allied disciplines and those from the realms of sociology, ecology, or anthropology in a conversation about the critical data sitting at the intersections between human behavior and technological innovation. In this paper, we review and discuss the state of the art research on digital twins to identify the disciplines dominating the narrative in the context of a sustainable built environment. We unpack a techno-rationalist view that emphasizes the sole reliance on technology for problem-solving and argue that by going beyond energy consumption and carbon emissions, digital twins can facilitate a more nuanced assessment of sustainability challenges, encompassing social equity, cultural preservation, and ecological resilience.*

KEYWORDS: *Digital twin, socio-ecology, sustainability, smart city, review.*

1. INTRODUCTION

The alarming effects of climate change and environmental degradation have prompted various global policies to set ambitious targets for reducing carbon emission by 2050 (Climate Change Committee, 2019; United Nations Environment Programme, 2022). The urgency of climate change as well as the recent pandemic have raised many questions of what the future of the built environment should look like and how that future can be envisioned and accomplished. Carbon emission targets or achieving "net zero" have thus prompted many digital transformation initiatives as a way to mobilize technology and data science to monitor, simulate and evaluate possible solutions across sectors to meet the decarbonization goals and improve overall performance. In the built environment disciplines and construction specifically, one such initiative that has attracted much attention is the concept of digital twins as a way to connect physical and digital assets to support data-driven decision making in complex environments. In the UK for example, the National Digital Twin Programme (CDBB, 2019), offers a broad vision of connected digital twins across environmental, social and economic spheres driven by an ultimate goal of enabling people and systems to flourish. This shift has also challenged built environment practitioners to consider the long-term consequences of any interventions (Whyte et al., 2020) and has led to a greater focus on outcomes rather than outputs, and a broader digital context within which project data can be situated, for example in the context of 'smart cities'.

Yet, given that the global demands for energy are increasing, the pursuit of carbon emissions reduction has consequently focused efforts on understanding and reducing energy consumption in the contexts of infrastructure and building performance. However, research points out that responding to the climate challenge is far more complex, or a "super-wicked" problem that defies simplistic technological solutions and often prioritizes short-term goals with competing priorities (Levin et al., 2012; Rabeneck, 2008). Achieving a truly sustainable built environment is much more complex, calling for approaches that transcend any single discipline and move away from project-bound methodologies to those where developed models span organizational and jurisdictional units (Whyte et al., 2019). As Rabeneck (2008) argues, any understanding of asset performance demands a systems perspective to better articulate needs within a given context. Initiatives such as the National Digital Twin in the UK and globally, begin to offer a long-term vision of interconnected, purpose-driven and outcome-focused digital twins, grounded in systems thinking. Such approaches recognize the economic, social and ecological layers as critical data components in these digital ecosystems for understanding the built environment as a whole. Yet, social and ecological sustainability will remain difficult to address without involving allied disciplines and those from

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Dragana Nikolic, Ian Ewart, *Going Beyond Energy Consumption: Digital Twins for Achieving Socio-Ecological Sustainability in the Built Environment*, pp. 1061-1071, DOI 10.36253/979-12-215-0289-3.106

the realms of sociology, ecology, or anthropology in a conversation about the critical data sitting at the intersections between human behavior and technological innovation.

In this exploratory paper, we review recent research around large-scale digital twins for the built environment and argue that while promoted as a potent industry-agnostic concept to support ambitious decarbonization goals, the narrative has been dominated by technology-focused methods to meet such goals. We identify literature that raises critical considerations for informing the holistic approaches to developing long-term purpose-driven digital twins for a sustainable environment. We review the relevant literature to unpack a techno-rationalist view that emphasizes the sole reliance on technology for problem-solving and argue that by going beyond energy consumption and carbon emissions, digital twins can facilitate a more nuanced assessment of sustainability challenges, encompassing social equity, cultural preservation, and ecological resilience. We explore a set of underlying assumptions and considerations such as the authority of the data, system complexity and cross-sector boundaries, and the technology landscape and procedures to enable constructive questioning. This approach allows us to understand how digital twin applications are subject to dominating business cases driving their development, which can consequently affect the design and operation of built environment projects. Moreover, we take the view that it is becoming increasingly difficult to sustain the traditional compartmentalized practices, but it is becoming imperative to promote conversations between the allied built environment and social disciplines to avoid single-issue dominance that could lead to unintended consequences, furthered by partially informed policies (Whyte et al., 2020). This has consequences for how digital technologies are used, demanding new and different kinds of data and processes, providing new challenges to the construction informatics research community and to practitioners.

2. THE SOCIO-TECHNICAL LANDSCAPE IN THE BUILT ENVIRONMENT

The pervasiveness of digital technologies across architecture, engineering, and construction practices as seen through a convergence of material science, robotics, 3D printing, sensors, artificial intelligence, and other technologies, presents new digital capabilities that connect physical environments with digital ecosystems. Technological innovation has always been paired with urban development (Quek et al., 2023), although in recent years, the concept of technology has shifted inexorably towards the digital and the view that the world, and reality itself is no longer analogue, but is made up of a digital representation of itself (Ewart, 2018). While the proliferation of low-cost consumer-market technologies paired with big data and Internet of Things has offered an enticing world of opportunities to improve the design, delivery, and operations of physical assets, it has also raised questions about how to make sense of the ever-growing raw and complex data sets to understand how we use the built environment and make informed decisions about its future (Nikolić & Whyte, 2021).

The concept of digital twins in the built environment practice has grown out of the recognition that the delivery of physical assets has become inseparable from the delivery of its digital counterpart and with a potential for an extensive data-capture to understand its use and improve its operation. With real-time asset data enabled, information received can influence future investment decisions, especially for serial clients such as governments, and aim to either change user behaviors or assets in new project interventions (Whyte & Nikolić, 2018). The digital twin idea was first introduced in 2002 in aerospace as a concept for Product Lifecycle Management (Grieves, 2019) and its use remains predominantly in manufacturing. Recent applications in the built environment include smart city initiatives, structural health monitoring, infrastructure planning and management (e.g. power, water, transportation), agriculture, and urban planning and development. In construction, the development of digital twins gained traction only in the last five years (Opoku et al., 2021), though not without challenges (Opoku et al., 2023). Urban infrastructure and 3D city models moving beyond geometry and information have started to become developed around the same time although mostly by linking BIM models with data (Ferré-Bigorra et al., 2022).

Unlike in the aerospace and manufacturing domains, digital twins for the built environment can span greater scales, professional domains and jurisdictional units, with an increasing complexity due to the heterogeneous data sources and sub-system interactions, leading to the difficulty of reliably predicting the system performance. For example, urban planning and management increasingly relies on understanding interactions between natural, cyber-physical and social systems in the form of urban digital twins (UDT) to foster human-centered resilience (Ye et al., 2023). Digital twins at city and urban scales can offer insight into how we use the built environment and inform the decisions for future interventions, yet their development is much more complex compared to DTs at building and component scales. Urban environments and cities are dynamic living systems that constantly evolve (Quek et al., 2023) and any interventions in this complex system will be intricately tied to economic and social sustainability goals as much as environmental. Ultimately, as Grieves (2019) argues, the success of digital twins will need to create value for the users of the systems, generally defined through value propositions or "use cases".

There is a tension between the grand challenge of setting broad sustainability goals and the practical challenge of a system-of-systems approach necessary for addressing them. For sustainable development, some of the recent reviews of digital twin applications and research (e.g. Papadonikolaki & Anumba, 2022) reveal that while holding a promise of a method to mitigate and adapt to environmental changes, the focus has been mostly on the decarbonization efforts in the energy sector and reducing energy consumption across the domains, including buildings. The research on design and delivery of buildings has encapsulated such efforts through increasing energy performance and reducing waste, although under the changing terminology of green, smart, high performance, carbon-neutral or net-zero buildings (Bonci et al., 2019; Gultekin et al., 2013; Korkmaz et al., 2010). A general survey of digital twin applications in design and construction domains, however, reflects rather an engineering approach to meeting decarbonization goals through improved sensing, monitoring, material, and data science, or predicting and simulating occupant behavior; and approach challenged by the view that the building performance is realized over time, rather than predetermined (Green & Sergeeva, 2020). The difficulty of such compartmentalized approaches and domain-specific definition of local carbon targets is that the outcomes may be insufficient to recognize the impact in a larger context and the system within which such interventions operate. As a result, most indicators developed so far have been primarily describing the state of the environment, rather than the relationship between society and ecosystems (Azar et al., 1996).

The dominating narrative around net-zero carbon has prompted predominantly technology-oriented approaches to decarbonization, whether they refer to extending renewable energy technologies or improving the energy performance of buildings and infrastructure. The global quest for smart products, buildings, cities and systems has been met with an ever-growing and more diversified digital ecosystem of software and siloed technological developments, a situation that has prompted calls for the technological dimension to be included in the sustainability trifecta of economic, environmental and social goals guiding the urban planning and development (Quek et al., 2023). However, Waring & Richerson (2011) argued that such environmental challenges are in fact, socio-ecological in nature and therefore, designing effective responses will depend on a deeper understanding of the human-environmental interactions. Socio-ecological perspective emphasizes societal activities that impact the use of resources, rather than on environmental quality indicators with an aim to aid in planning and decision-making processes at various administrative levels (Azar et al., 1996). Ince (2023) further suggests that adopting a socio-ecological approach and systems thinking with a multidisciplinary perspective can offer new models for creating systemic and long-term solutions to sustainability problems. In practice, this would mean thinking and modeling that involves all stakeholders, performing economic and biological analyses of the environment and resources at micro- and macro scales, and participatory approaches to environmental policy design (Ince, 2023). Such perspectives invite dynamic systems thinking approaches that span spatial, temporal and organizational scales and considers a set of critical resources such as natural, social, economic and cultural, all located at the intersection of interdisciplinary collaboration, moving away from short-term narrowly focused technological fixes. In this context, there is somewhat of a paradox of technological optimism where technical fixes are viewed as solutions to all problems, even those that are non-technical in nature, while social and economic factors are viewed as obstacles, rather than essential to designing solutions (Rudolph, 2023). This is further exacerbated by the plethora of isolated pilot studies and the dominance of industry-backed funded research which is unlikely to lead to truly transformative socio-ecological thinking of transdisciplinary work (Rudolph, 2023).

3. METHOD

To explore the current narratives in research associated with socio-ecological systems thinking in the domain of digital twins, we conducted an initial level of a systematic review where we first identified bibliographical sources that focus on urban or city digital twins as we were interested in the broader scale digital twins to understand the system complexity. In the search, we excluded studies that were in the physical science areas, such as mathematics, physics, chemistry or medicine. We conducted a search of the Scopus database to sample articles and studies using the following sampling string:

TITLE-ABS-KEY ("city" OR "urban" OR "built environment" OR "smart city" AND "digital twin") AND TITLE-ABS-KEY ("social" OR "ecolog*" OR "sustainab*" OR "net-zero") AND

(LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp")) AND (LIMIT-TO (LANGUAGE , "english")) AND (EXCLUDE (SUBJAREA , "phys") OR EXCLUDE (SUBJAREA , "math") OR EXCLUDE (SUBJAREA , "medi") OR EXCLUDE (SUBJAREA , "ceng") OR EXCLUDE (SUBJAREA , "neur") OR EXCLUDE (SUBJAREA , "chem"))

The search yielded 153 publications including journal articles (92) and conference papers (61), all published between 2018-2023 (Fig. 1). Publications in the area of social science are among top five, flanked by those in the areas of engineering, computer and environmental sciences, and energy (Fig. 2). Lastly, it was interesting to observe that the significant funding in this area comes from the European funding schemes, followed by the national science funding programs in the U.S. and China (Fig. 3).

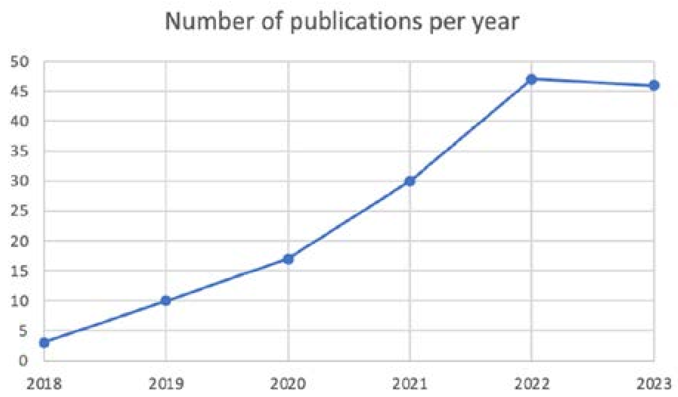

Fig. 1: Number of publications on urban and city digital twins per year

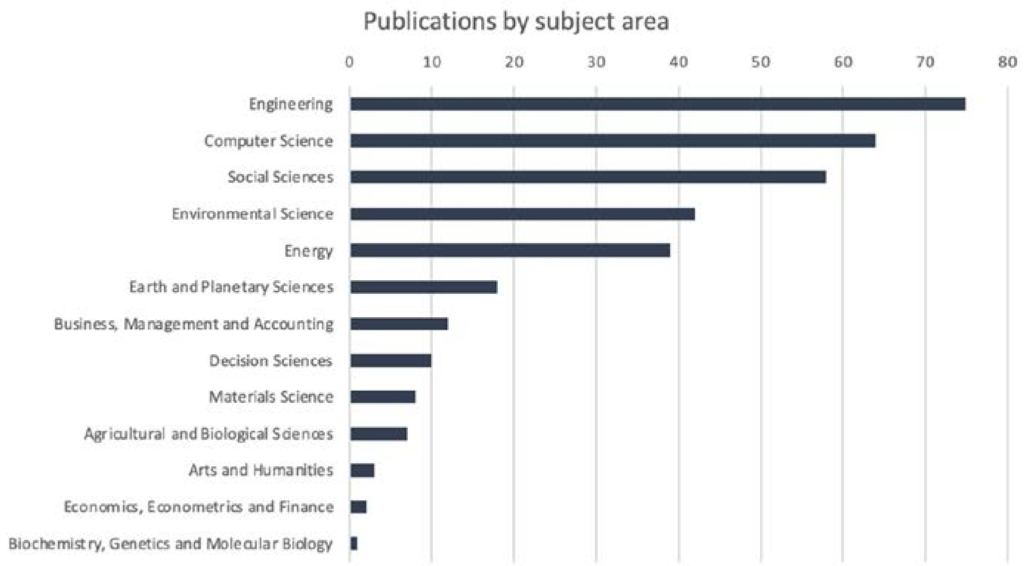

Fig. 2: Number of publications on urban and city digital twins per year

Fig. 3: Publications by funding sponsor

However, the review of abstracts revealed a wide range of approaches and methods with a high degree of varying conceptualization of problems and definition of digital twins, leading to a considerable number of papers being omitted from further review. For example, papers that approached digital twin models from an engineering perspective or conceptualized them as a single system with no links made to either social or ecological issues were out of scope (e.g. water system focusing on flood risks). Similarly, papers focusing only on economic, technological or social aspects were omitted as well. Lastly, papers that only focused on digital models that did not interact with their physical counterpart were not considered to be digital twins as defined. This has led to a list of 25 publications that were selected for further review to identify themes, considerations, developments and challenges for developing complex socio-ecologically driven digital twins (Table 1).

Table 1: Select publications with key data.

No	Reference	Title	Type	Focus
1	Yigitcanlar T. et al. (2019)	The making of smart cities: Are Songdo, Masdar, Amsterdam, San Francisco and Brisbane the best we could build?	Article	Multidimensional framework
2	Sadowski J. and Bendor R. (2019)	Selling Smartness: Corporate Narratives and the Smart City as a Sociotechnical Imaginary	Article	Counter-narrative of technology salvation
3	Dembski F., et al. (2020)	Urban digital twins for smart cities and citizens: The case study of Herrenberg, Germany	Article	Practical use of UDT and part. engagement
4	Goel R.K., et al. (2021)	Self-sustainable smart cities: Socio-spatial society using participative bottom-up and cognitive top-down approach	Article	behavioral intellig., trans-disc knowledge
5	Shahat E. et al. (2021)	City Digital Twin Potentials: A Review and Research Agenda	Article	incl. of socio-econ. components
6	Yossef B. & Aharon-Gutman M. (2022)	The Social Digital Twin: The Social Turn in the Field of Smart Cities	Article	Complexity theory
7	Benedetti A.C., et al. (2022)	The Process of Digitalization of the Urban Environment for the Development of Sustainable and Circular Cities: A Case Study of Bologna, Italy	Article	Predictive tool for urban planning
8	Tzachor A., et al. (2022)	Potential and limitations of digital twins to achieve the Sustainable Development Goals	Article	modeling socio-technical and socio-ecological systems
9	Corrado C.R. et al. (2022)	Combining Green Metrics and Digital Twins for Sustainability Planning and Governance of Smart Buildings and Cities	Article	metric-driven framework for sustainability planning of a sociotechnical system
10	Charitonidou M. (2022)	Urban scale digital twins in data-driven society: Challenging digital universalism in urban planning decision-making	Article	socio-tech. perspective of smart cities
11	Ferré-Bigorra J. et al. (2022)	The adoption of urban digital twins	Article	limitations of city digital twins
12	Bozeman J.F. et al. (2023)	Three research priorities for just and sustainable urban systems: Now is the time to refocus	Article	social equity and justice, circularity, and DTs
13	Ye X. et al. (2023)	Developing Human-Centered Urban Digital Twins for Community Infrastructure Resilience: A Research Agenda	Article	human-centered UDTs framework
14	Peters, D. and Schindler, S. (2023)	FAIR for digital twins	Article	sustainable data landscape
15	Kumalasari D. et al. (2023)	Planning Walkable Cities: Generative Design Approach towards Digital Twin Implementation	Article	human perspective in scenario development
16	Al-Sehrawy R. et al. (2023)	The pluralism of digital twins for urban management: Bridging theory and practice	Article	DT inconsistencies and poorly measured priorities
17	Masoumi H. et al. (2023)	City Digital Twins: their maturity level and differentiation from 3D city models	Article	going beyond 3D viz. an, monitoring
18	Quek H.Y. et al. (2023)	The conundrum in smart city governance: Interoperability and compatibility in an ever-growing ecosystem of digital twins	Article	systems and semantic integration
19	Dembski F. et al. (2019)	The Digital Twin Tackling Urban Challenges with Models, Spatial Analysis and Numerical Simulations in Immersive Virtual Environments	Conf paper	civic engagement in urban planning
20	Wan L. et al. (2019)	Developing a city-level digital twin - Propositions and a case study	Conf paper	theory and policy experimentation
21	Mohammadi N., et al. (2020)	Knowledge discovery in smart city digital twins	Conf paper	spatiotemporal knowledge discovery framework
22	Yue A. et al. (2022)	Smart Governance of Urban Ecological Environment Driven by Digital Twin Technology: A Case Study on the Ecological Restoration and Management in S island of Chongqing	Conf paper	Urban restoration
23	Zou S. et al. (2022)	A Preliminary Study on the Development and Application of Digital Twin Landscape Architectures in the Context of Smart City	Conf paper	digital twin landscape architecture
24	Akimov L. et al. (2023)	The Environmentally-Efficient Canal District Design Respecting Urban Context	Conf paper	landscape restoration
25	Cruz P. et al. (2023)	Towards e-Cities: An Atlas to Enhance the Public Realm Through Interactive Urban Cyber-Physical Devices	Conf paper	heterogeneous urban cyber-physical projects case studies

4. EMERGING THEMES AND THE DISCUSSION

The select list of publications demonstrates that the research focusing on large scale digital twins is still in early stages and some of the relevant discussions and debates remain largely embedded within the "smart city" literature. From the select list of publications, we sought to identify the application areas, as well as the indicators of the systems thinking that extend the environmental performance. In doing so, our goal was to establish the extent of socio-ecological and transdisciplinary thinking informing the development of large-scale digital twins and the potential obstacles for their implementation.

4.1 Urban digital twins and smart cities

Digital twins at urban scales have been tightly coupled with the smart city narratives where the focus has been largely on modeling specific infrastructure needs that include forecasting and preventing of floods, increasing the efficiency of power grids, understanding of commuting patterns for transportation, as well as modeling and prevention of epidemics in the public health domain. From the literature, such digital twins have been variably termed city digital twins (CDT), urban digital twins (UDT), or social urban digital twins (SUDT). The greatest challenge, however, is determining how closely the digital twin should be coupled with the real urban environment and whether the abstraction and simplification of social or economic datasets could even qualify such models as digital twins (Ye et al., 2023). While the promise and the potential for city digital twins to not only mirror and interact with the physical counterpart, but also account for social and economic aspects (Wan et al., 2019), fewer studies elaborate on the complexity of developing such models or describe the interactions and dependencies between the heterogeneous data sets spanning spatial and temporal description of environmental, social, and economic factors (Savage et al., 2022). Although digital twins of cities have been developed, it is difficult to discern with consistency what systems have been modeled in each implementation and to what extent, further confusing the understanding of urban or city digital twins (Ferré-Bigorra et al., 2022).

What has also become apparent from the review is that the discussion of city, or urban digital twins is tightly coupled with the smart city narratives. The relationship between city digital twins and smart cities is not yet clear, although the smart city conceptualization as technology-assisted and connected infrastructure and communities through sensors and automation closely resembles that of a digital twin. In that context, both digital twins and smart cities that are deemed to be successful are those that adopt a system of systems approach and balance the sociocultural, geospatial, and institutional perspectives of cities beyond the means of technology solutions (Quek et al., 2023; Yigitcanlar et al., 2019). Yigitcanlar et al. (2019) offer a multidimensional conceptual framework that centers on urban policy to inform urban planning and development where innovation economy, socioeconomic equality, ecological sustainability and (smart) governance, each equipped with their own performance indicators, are all critical for building smart cities.

Some studies expand the use of urban digital twins with sociological approaches by focusing on social issues such as urban aging and gentrification, poverty, or other social disparities, termed as social urban digital twins (SUDT) (Sadowski & Bendor, 2019; Yossef Ravid & Aharon-Gutman, 2023). Such studies exemplify attempts to integrate social fabric with the built urban space, although not without raising ethical and legal questions behind the need to collect social data, currently the focus of the field of Digital Sociology (Lupton, 2015). At the same time, the criticism of such developments is based on observations that corporations tend to reframe urban sustainability challenges that favor narrow economic gains at the expense of socio-ecological sustainability, especially in the context of energy consumption and smart grids (Evans et al., 2019; Quek et al., 2023). Nevertheless, all the city digital twin developments testify to the complexity of replicating such complex and evolving systems, even at the physical levels, which is perhaps one of the reasons for the adoption of technocratic approaches that ignore wider social and environmental factors (Kitchin, 2014; Semeraro et al., 2021).

4.2 Technological optimism and implementation reality

The development of large-scale city digital twins generally involves the integration of 2D and 3D information and data models, such as BIM or GIS, and data sources, such as sensors, Internet of Things, and other solutions that form the physical, network and computing layers (Quek et al., 2023; Semeraro et al., 2021). Research on large scale city and urban digital twins remains more focused on the software side of modeling the physical environment, rather than on participatory planning and policymaking informed by human-centered behavior analysis, an approach that would enable planners and policy makers to understand the knock-on effects of environmental changes on social resilience (Ye et al., 2023). As the complexity of urban systems that need to be modeled and integrated is increasing, so has increased the rate of various siloed technological developments, posing new challenges for the city administrations and governance. It has been widely recognized that city digital twins will require a transition from single institutions to scalable solutions where multiple professional domains contribute the data and inform the relevant analyses (Savage et al., 2022). The technical complexity of integrating various data formats, applications, systems and other sub-system DTs has consequently drawn much more attention to the technological considerations for resolving such issues. The proliferation of various public and private technological research and development efforts have further diversified the digital ecosystem at the expense of knowledge sharing and cross-domain collaboration, leaving the development of city digital twins in their infancy (Shahat et al., 2021).

Though technological challenges remain important to be resolved, the field of smart city and digital twin developments have become progressively critiqued for their heavy reliance on technologies as means to manage urban and environmental crises (e.g. Nochta et al., 2019; Yossef Ravid & Aharon-Gutman, 2023). Advanced smart city initiatives, such as Singapore[1] or Beijing[2] for example, increasingly embed new technologies into city design, retrofitting or upgrading their infrastructure, which presents challenges for the city's phased developments and the pace of technological developments. As Quek et al. (2023) illustrate, cities develop at a much slower pace than technologies, whereby the time projects are completed, the technology solutions may well become outdated. This further exacerbates the existing challenges of integration, interoperability, and compatibility, perpetuating the cycle of pursuing technological solutions to technology-created problems. Some studies have pointed out the challenge of profit-driven corporate interests seeping into the social realm by appropriating and dominating the narrative of urban challenges and technological fixes (Sadowski & Bendor, 2019; Yossef Ravid & Aharon-Gutman, 2023). This complex technological influence on urban governance where social perspective has been largely absent, presents academics, professionals and policy makers with a real challenge of working together to enable outcome-based and value-driven decision making that drives more comprehensive social, environmental and economic values. The ever-growing digital ecosystem of various digital twin technology solutions has consequently raised several practical challenges that extend those of interoperability alone.

4.3 Practical challenges for socio-ecological and systems thinking

The review of studies revealed a number of both technological and strategic challenges facing the development of large scale complex digital twins for addressing socio-ecological and environmental goals. These have been broadly categorized into three categories (Table 2) and described further below.

Table 2: Overview of select hindrances to the development of large-scale digital twins.

Category	Issues	Description
Data	Volume/Quality	Overproduction of unusable data vs. co-production of socially relevant information; data quality; data errors
	Bias	Selection bias or misrepresentation of marginalized communities in the design and deployment of digital twins
	Availability/Ethics	Private, proprietary or other sensitive data, especially social data; security, legal and commercial boundaries
	Heterogeneity	Domain-specific data types and formats; qualitative vs. quantitative; static vs. dynamic; coding and structuring approaches
	Reusability	Lessons learned recorded in a machine-readable form; cross-pollination or knowledge between projects and domains
	Ownership	Enable individuals and communities to envisage and understand data on a human scale; calibration of citizens data
Model	Complexity	Physical, social, ecological datasets; dynamic spatial-temporal and socio-ecological changes
	Optimization	Model assumptions are clear; data are transparent; trade-offs and contradictions between different targets and outcomes
Integration	Siloed development	Within the design, social, and engineering sciences; between research and practice; techno-rationalism and corporatization of technology
	Interoperability	Integrating multiple GIS, BIM, CIM, 2D and 3D data models; individual technology solutions
	Digital divide	DT development and integration bound to the available investments and resources at district, region or country levels

Data is the basis of all digital twins and generating, accessing, filtering, analyzing and using relevant data presents an array of different challenges for the development and usability of digital twins. There is a general consensus across the literature that the overproduction of data, either from the projects or sensors and users, is a problem, prompting an increasing reliance on machine learning and artificial intelligence to process and make sense of the ever growing volumes of raw data. This vast and unfettered production of data also signals the separation between the digital and the human where the suggestion that one of the benefits of the digital revolution is the production of 'big data', becomes dangerous without recognizing our limited ability to make use of it (Ewart, 2018). On the other hand, the needed data may not be easily available due to privacy or proprietary issues.

[1] https://www.smartnation.gov.sg

[2] https://www.beijingcitylab.com/projects-1/43-smart-cities-review/

Most instances of urban digital twins developments are based in 3D models, while the integration of 2D information and non-graphical data is far more sporadic. Ye et al. (2023) in their review demonstrate how multidimensional visualization of integrated social sensing data, land-use change and demand models for example, while essential for planning of future urban landscape, is largely missing. Furthermore, data use is driven by the purpose of their primary users reflecting an inherent bias, even when data are quantitative (Nikolić & Whyte, 2021). In addition, different coding schemes used across the professional domains for describing and structuring the data complicates efforts to automate the querying of data (Peters & Schindler, 2023). Still, planning and design approaches, especially at broad urban, social, and environmental scales, involve consideration of a range of factors, uncertainties, and conflicting goals, all largely part of a decision-making process of which automation is not yet capable (Allam & Dhunny, 2019).

The difficulty of simulating complex systems of systems, such as urban environments has long been debated where some have questioned the value of digital twins in the face of simpler monitoring systems (Ferré-Bigorra et al., 2022). Complexity theory has surfaced as a conceptual framework for studying and designing smart cities (e.g. (Yossef Ravid & Aharon-Gutman, 2023) to help deal with issues of uncertainty, diversity and emergence and inform policies on ways to cope with unpredictable behavior of urban systems. Creating digital twins with a socio-ecological focus necessitates inputs not only from the allied built environment disciplines, but also from the fields of sociology, anthropology, ecology and planning, which still remains short in supply. The importance of such approaches informing policies is illustrated by Savage et al. (2022) where the changes in energy consumption patterns resulting from a combination of measures in carbon tax, technology adoption and land use data would affect social inequality in the UK.

Resulting from the challenges above, the integration of data, models and approaches across domains and scales perhaps remains the over compassing challenge to the development of complex and connected digital twins. Integration of diverse datasets, models and methods that better account for differences in human behaviors further remain underexplored (Delmelle, 2021). It is clear that future tools will have to incorporate different types of data from a variety of domains. This however, does not even account for the computational resources needed to process such large and complex datasets. The remaining controversy is the viability of urban digital twins and whether they can ever truly represent the intra- and inter-social complexity of socio-technical and socio-ecological systems, especially those that incorporate societal elements (Batty, 2018).

5. CONCLUSIONS

The twin urgency of climate change and sustainable development have propelled explorations of large scale urban digital twins as a data-centric, cross-disciplinary platform that could promote better decisions through mutual learning, public participation and stakeholder engagement. The concept of urban digital twins and the value of data sharing across sector boundaries has been recognized in the UK through a National Digital Twin program (CDBB, 2019). Research, however, demonstrates that the urban digital twin conceptualization, development, and implementation are still very much in their infancy, while the narratives intersect with those of smart cities. Urban environments with a complex interplay of spatial, social, environmental, and economic factors have proven challenging for the digital "twinning", leaving most digital twin developments stopping short of modeling socio-ecological and socio-technical systems. When designed well, city digital twins, as other technologies, should support human agency and democratize the decision-making process, shifting the balance of authority away from the experts alone. Yet, despite their great potential and promise they hold, the vast technological bottlenecks exemplified in the issues of data, interoperability, federation, integration, scalability or futureproofing of technological solutions have all focused much attention on resolving such issues and at the expense of exploring and including the socio-ecological dimensions that may impact the planning and development of scenarios.

While sustainability encompasses environmental, social and economic aspects, the literature review demonstrates a predominant focus on the potential of digital twins to achieve decarbonization goals through carbon and energy consumption metrics. In this paper, we began by mapping the latest research on large-scale DT applications across domains to describe the elements of the dominant narratives for informing future changes in the built environment and addressing the challenges of sustainable development and social resilience. Although socio-ecological perspective extends the sustainability trifecta by promoting systems thinking and offering new theory necessitating multidisciplinary management approaches, we illustrated how the urban and city digital twin developments remain largely domain-specific where projects are yet to be seen as interventions within larger complex systems.

Finally, while digital twins offer powerful and novel ways to engage diverse disciplines in shared conversations, fragmented practices are maintained not only within traditional and institutionalized modes of working, but also discipline-specific tools and technologies designed to handle data at different scales and data needs. Integrating such diverse data sets not only requires overcoming issues of interoperability, but also crafting new narratives around salient spatial, social, and ecological features aimed at the users most likely to have a say in decisions with longer term consequences.

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APPLICATION OF THE INTERNET OF THINGS (IoT) FOR ENERGY EFFICIENCY IN BUILDINGS: A BIBLIOMETRIC REVIEW

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ABSTRACT: *Buildings are experiencing tremendous transformation, where Internet of things (IoT) is been used to transform traditional buildings into smart structures. While there are viable IoT techniques, developing IoT applications and operations to fully realise the technology's promise is needed. This may be done successfully by bridging the gaps in the present research to establish a foundation for future investigations. This study analysed extant literature in IoT (between 2008 and 2022) through a bibliometric review to tease out critical measures for their integration and transformation. The study adopted a science mapping quantitative literature review approach and employed bibliometric and visualisation techniques to systematically investigate data. The Scopus database was used to collect data and VOSviewer software to analyse the data collected to determine the strengths, weights, clusters, research trends in IoT. Important findings emerging from the study include recent literature by various researchers on IoT applications in buildings. The shift in recent patterns of research from developed to developing countries. Eighty-nine (89) keywords were analysed and divided into six clusters. Each cluster is discussed to present its research area and associated future studies in relation to Smart buildings. This paper uses bibliometric analysis to unpick recent trends in IoT and its relevant application to buildings. The paper provides a blueprint for future IoT research and practice, needed awareness and future strategy directions for IoT applications in construction. This creates opportunities to transition to more sustainable construction sector.*

KEYWORDS: *Bibliometric review, Energy efficient buildings, IOT (Internet of Things), Literature review, Smart buildings, sustainability, science mapping.*

1. INTRODUCTION

Massive challenges caused by rapid digitalization have greatly increased the demand for energy (Al-Obaidi et al., 2022). Energy consumption around the world is estimated to increase by 56% in 2040 (Energy Information Administration (EIA), 2013). Internationally, there are efforts to reduce energy consumption in buildings and cities such as the EU's 2050 roadmap which aims to lessen energy and gas emissions by approximately 40% (Fragkos et al., 2017). Buildings, both residential and commercial, have played critical roles in human existence by providing convenient, safe, and satisfying venues for emotional, physical, and social requirements. Building inhabitants should constantly feel secure and protected, since this might affect their general well-being and productivity (Lawal & Rafsanjani, 2022). As a result, real-time monitoring, control, and management of a building and its inhabitants, components, appliances, systems, environment, and health is critical (Rafsanjani et al., 2018; Ghahramani et al., 2020). This emphasizes the need of automation in both household and business settings. Smart buildings are unique structures that employ intelligent automation for their operations to provide efficient, pleasant, and secure environments for its users. Building automation utilizing the Internet of Things (IoT), a renowned advanced technology, can provide cutting-edge solutions for strengthening security and safety, remoting appliances/systems, monitoring occupants, increasing efficiency, and improving visual and thermal comfort (Kanan et al., 2018; Saha et al., 2018).

Although there have been various literature on IoT in the context of the buildings (Gholamzadehmi et al., 2020; Al-Obaidi et al., 2022; Wang et al., 2021; Bola et al., 2019; Mataloto, Ferreira & Cruz, 2019; Lawal & Rafsanjani, 2022), only few studies have sought to summarize the existing research using bibliometric techniques. For example, Gholamzadehmi et al. (2020) conducted a review of adaptive-predictive control strategy for heating ventilation and air conditioning (HVAC) systems in smart buildings. However, the scope of their study on smart buildings is focused solely on smart control of building energy services. Al-Obaidi et al. (2022) carried out a systematic review of IoT for energy efficient buildings and cities from a built environment perspective analyzing

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Nnaemeka Nwankwo, Ezekiel Chinyio, Emmanuel Daniel, Louis Gyoh, *Application of the Internet of Things (IoT) for Energy Efficiency in Buildings: A Bibliometric Review.*, pp. 1072-1084, DOI 10.36253/979-12-215-0289-3.107

literature published between 2020-2022. However, their study scope is too broad and lacks exclusive statistical or quantitative focus on IoT research based on buildings. Bola et al. (2019) presented a critical survey of IoT based automated energy management in buildings. They reviewed various IoT applications in the area of building energy management and energy consumption data were recorded, which they highlight as a very important consideration in system planning and rehabilitation. Mataloto et al. (2019) presented efforts on optimizing energy consumption in buildings by use of an IoT based platform known as LoBEMS (Lora Building and energy management system). They developed an approach that helps local administration entities identify savings from personalized data visualization. Wang et al. (2021) conducted a thorough analysis of the extant literature on IoT and edge computing in different application fields, including smart homes and smart cities. Lastly, Lawal and Rafsanjani (2022) applied a systematic review while exploring the trends, benefits, risk and challenges of IoT implementation in residential and commercial buildings and highlighted that IoT is a crucial driver for the evolution of various types of buildings.

Even though each of these reviews provides a wealth of valuable insights, no thorough and timely review utilizing bibliometrics, focused solely on smart buildings can be found in the literature, which presents an important research gap. Since the academic literature in the field of IoT has had significant growth, the application of a quantitative review approach is required to better understand the knowledge structure of the field (Rivera & Pizam, 2015). Researchers should try to occasionally examine the accumulated body of knowledge as study fields develop and become more complex according to Ferreira et al. (2014), as well as understand new contributions, research trends and traditions, topics being studied and investigative the structure of knowledge and future research directions.

This study analyses extant literature in IOT and its application to buildings (between 2008 to 2022) through a bibliometric review, to tease out critical measures for their integration and transformation. The objectives are to evaluate the global research trends of IOT application in construction based on citation analysis of countries and co-occurrences analysis of author keywords cluster, using Vosviewer document analytic software and Scopus database. The study findings would benefit the academic community as it contributes to (1) providing valuable directions by examining the bibliometric status of IOT in the built environment sector from the existing literature, identifying the knowledge areas with links for their integration and (2) identifying the critical areas needed to advance IOT application in buildings in future studies and to support practical implementation.

2. METHODOLOGY

Researchers commonly employ three approaches to evaluate literature, according to Zupic and Cater (2015): (1) a qualitative approach of a systematic literature review, (2) a quantitative approach via meta-analysis, and (3) science mapping (based on the quantitative approach utilizing bibliometric methodologies). The third technique is viewed as the most suited for assessing the state-of-the-art literature of a research topic and is quickly becoming increasingly popular in numerous disciplines of study (Tavares-Lehmann & Varum, 2021). Science mapping uses bibliometric approaches such as citation analysis to assist academics in identifying trends in the structure and dynamics of scientific subject topics. Using the bibliometric approach in scientific literature reviews enhances rigor and lowers researcher bias (Cavalieri et al., 2021). It is superior to typical literature reviews in that it provides for a more objective and methodical selection and assessment of scientific research on a specific topic (Cobo et al., 2015). To fulfil the study's goals and objectives, we used a bibliometric technique that includes three stages of review: (1) data collecting, (2) analysis and visualization, and (3) interpretation, like a prior study by (Obi et al., 2023).

2.1 Data collection

A search query, selection of relevant database(s), and data screening are all part of the data collecting process (Ari & Cuccurullo, 2017). Employing the correct search phrases in a bibliometric study is important to success (Obi et al., 2023). According to Lawal and Rafsanjani (2022) we followed the search terms for IOT application in buildings. They chose keywords for the IOT research after conducting a thorough review of earlier relevant studies on the definition and application of IOT in various kinds of residential and commercial buildings and they compiled a list of important terms that are used interchangeably. As a result, a mixture of appropriate search phrases was employed, and the whole search code is as follows:

“IOT buildings” OR “Internet of Things buildings” OR “smart buildings” OR “Intelligent Buildings” OR “automated buildings”.

We identified a database that contained bibliometric data. Scopus and Web of Science (WoS) are now prominent databases for retrieving publications (Obi et al., 2023). The Scopus database was used to extract and collect bibliographic data for the study. Scopus is a digital bibliographic platform widely recognized for high quality standards and a frequent instrument for doing construction-related bibliometric research (Patel et al.,2021). Rani and Kumar (2022) conducted bibliographic analyses and identified Scopus as a favored alternative for IOT application review research. Similarly, recent literature reviews in IOT research (Lawal & Rafsanjani, 2022; Al-Obaidi et al., 2022) have employed the Scopus database.

To screen the obtained data, we used a set of inclusion and exclusion criteria (relevance, language, and quality). A total of 26,512 papers were returned because of the search in the Scopus core collection. The publication period was limited to 2008 to present (2022) and was chosen because the classification by year of publication shows a growing trend of articles published in relation to IOT within this period. **Figure 1** shows distribution of articles by year of publication. From this image it can be said that publication on IoT related to building applications picked up in 2005 and had a more significant number of publications from the year 2008. The year 2008 recorded 52 articles whilst the subsequent years recorded a rise in the number of articles published progressively and considering the increasing number of articles over the years, with the constant rise in publications, it can be inferred that literature on IOT application will continue to increase in years to come.

Finally, Papers from subject areas with no strong affiliation to application of IoT in buildings like chemistry and decision sciences were eliminated. Non-English publications in the relevant topic areas were removed to avoid translation difficulties and to decrease ambiguity in essential ideas. Associated keywords presented by Scopus because of searching for relevant documents were skimmed through to identify duplicates and words with no strong link to the research area were subsequently excluded. To ensure the quality of the papers utilized, only peer-reviewed article publications and reviews were included. After that, the author performed further skim readings of the title, abstract, and selected document, resulting in the elimination of papers not connected to IOT application in buildings. Applying the relevance, language and quality criteria resulted to 21,637 papers being deleted during the process, leaving 4,875 articles used for the analysis. These articles were then exported to excel from Scopus (in the order of most cited to least cited documents) to allow the implementation of an analysis software (VOSviewer).

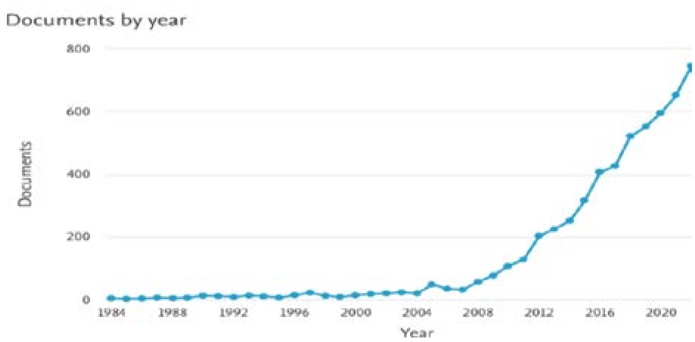

Fig. 1: Showing a growing trend of research on IoT application to construction. (Source: scopus).

2.2 Data analysis and visualization

This paper makes use of citation and co-occurrence analysis. Commonly used bibliometric methodologies, according to Mas-Tur et al. (2021), are:

(1) Co-occurrence analysis which evaluates the conceptual structure of knowledge in the subject, finding relevant keywords and themes related with the primary concepts of research.

(2) Citation analysis estimates the impact of publications, authors, journals, or nations based on citation rates.

The bibliographic information was presented using the visualization of similarities (VOS) viewer software version 1.6.19. VOSviewer allows you to map, visualize, and identify the network structure in research (Leydesdorff & Nerghes, 2017). Because of the ease of understanding, presentation, and visualization of the maps, it was chosen above other regularly used tools such as Pajek and Citespace. The network is composed of distance-based maps, with the distance between two elements reflecting the intensity of their link. A shorter duration often suggests a stronger bond. The size of the item label reflects the number of instances of the phrase discovered. A bigger label size indicates that the related item appears in more publications, while various colours reflect distinct groupings of items aggregated by VOSviewer's clustering approach (Yin et al., 2019).

3. RESULT AND DISCUSSION DATA ANALYSIS AND VISUALISATION

This section presents the bibliometric and network analysis results as tables and networks and a discussion of the various results gotten from the analysis.

3.1 Citation analysis

Citation analysis is used to identify high-impact journals and significant nations in IoT research. The number of publications and citations are used to assess the influence and quality of research in a certain topic (Wuni et al., 2020).

3.1.1 Countries involved in researching the application of IoT in construction.

The minimal number of citations and publications was set at 10 and 5 respectively, using VOSviewer. This was done to guarantee that only nations that are actively engaged in research on IOT application for buildings are chosen. 72 out of the 160 nations available were chosen to meet the criteria; the findings of the analysis are shown in **Figure 2**. There are 10 most productive countries leading in research on IoT in relation to building applications. The republic of China with a total of 730 documents and 35,390 citations. It is followed by United States of America with a total of 716 documents as well as other nations within the top ten as shown in **Table 1.** Among the ten nations China and India are the only developing countries, which is similar to results gotten in a review study by (Al-Obaidi et al., 2022).

Table 1: Top 10 most productive countries involved in the research of IoT application to building construction.

Country	**Document**	**Citation**
China	730	35,390
United States of America	716	21,163
United Kingdom	323	14,280
Italy	260	11,550
South Korea	226	8,480
India	225	6,343
Canada	195	10,701
Australia	182	6,612
Spain	164	5,942
Germany	156	6,450

The closer the colour is too yellow, the recent the investigation is in literature, as seen in **Figure 2,** from countries like United States, Morocco, Nigeria and Pakistan. This demonstrates that recent study patterns are majorly researched by developed nations but are also shifting towards developing countries, particularly those seeking sustainable and energy efficient improvements in their building industry, highlighting the need for more empirical research in these developing countries.

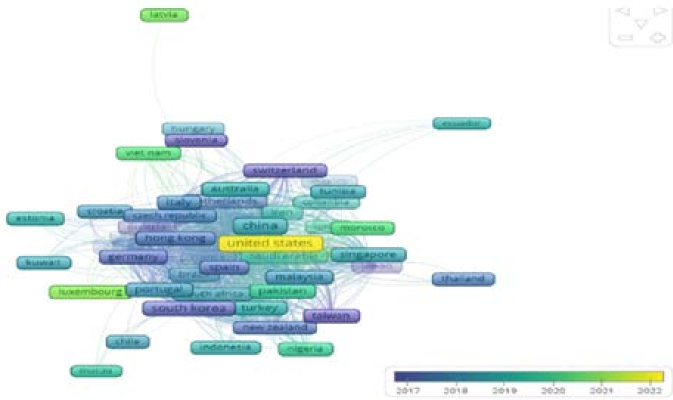

Fig. 2: Vosviewer map of countries associated with the application of IoT in construction.

3.2 Co-occurrence analysis on IoT application in construction

Co-occurrence, highlights keywords and have an important role in bibliometric analysis. According to Van Eck and Waltman (2014), author keywords should be used for bibliometric analysis to show patterns in current research. As a result, author keywords were chosen as the foundation for the current study's co-occurrence maps. The threshold of occurrences of a keyword was chosen at 15 based on recent bibliometric literature review (Baghalzadeh Shishehgarkhaneh et al., 2022). Repeated terms (for example ("smart house" and "smart homes") were eliminated. The criteria for the study were fulfilled by 89 of the 10,008 keywords. The co-occurrence network's large nodes (frames) and colour presentations, as well as the primary linkages, were investigated to analyse the research hotspots and concerns dominating IoT literature. The cluster formation was used in the co-occurrence analysis.

3.2.1 Co-occurrence of author keyword by cluster

The keywords "Smart buildings", "Energy efficiency" and "Internet of Things" have large nodes in the network as seen in **Figure 3**, indicating researchers have been more interested in studying these areas of research and their similar concepts. Six clusters, as shown in **Figure 3** emerge following the analysis.

Cluster 1 (IoT based sustainable construction design): It is in red and the largest cluster with 28 items: building energy efficiency, green building, building information model, thermal energy storage, solar energy are some of the relevant keywords in this cluster. This cluster indicated a strong focus on sustainable construction design in relation to IOT application to buildings. From a design perspective extensive IoT research has focused on Building energy efficiency, especially due to this area of research been one of the main goals of construction design (Lawal & Rafsanjani, 2022).

Cluster 2 (Building automation system): It is green with 17 items; building energy management system, anomaly detection, building automation, model predictive control, building control, hvac, indoor air quality and thermal comfort are some of the relevant keywords emerging from this cluster. This cluster is concerned with IoT based building automation systems and the efficient control and management of building energy services.

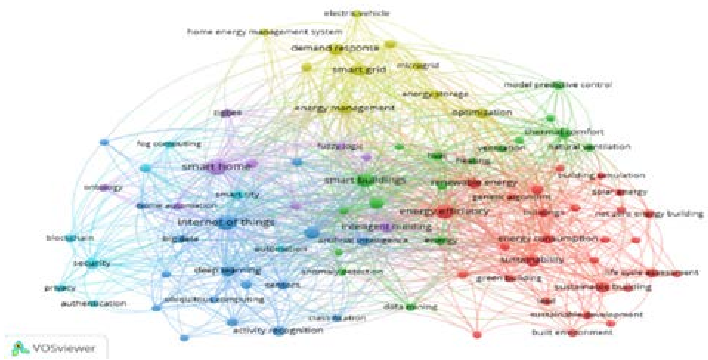

Fig. 3: keyword network visualization by cluster

Cluster 3 (AI in smart buildings): It is in blue and is made up of 17 items: machine learning, sensors, AI (artificial intelligence), internet of things, activity recognition, ambient intelligence, big data are some relevant keywords from this cluster. This cluster highlights the core operational principles of IoT, it explores the concept of AI and its contribution to the realisation of smart buildings.

Cluster 4 (IoT for efficient energy management in buildings); It is yellow and includes 10 items; Energy management, demand response, smart grid, micro grid and home energy management system are some of the relevant keywords. This cluster highlights various technical functions of an IoT system to efficiently manage energy consumption in buildings.

Cluster 5 (Improved quality-of-service in smart buildings); It is purple and includes 9 items; wireless sensor network, neural network and Interoperability are some of the relevant keywords in this cluster. This cluster highlights the improved quality-of-service offered by IoT networks to smart building occupants or smart users.

Cluster 6 (Blockchain in smart buildings); It is light blue in colour and includes 8 items; authentication, blockchain, smart city, privacy and security are some of the relevant keywords in this cluster. This cluster is centered around the use of blockchain in IoT based smart building systems and the role of the technology in protecting user privacy and safeguarding information that flows through IoT devices or nodes.

4. DISCUSSION OF CLUSTERS AND FUTURE RESEARCH DIRECTION

In this section, the six study fields (Blockchain in smart buildings, AI in smart buildings, IoT for efficient energy management, Improved quality-of-service in smart buildings, building automation and IoT based sustainable construction design) emerging from the results of the co-occurrence cluster analysis are discussed. The knowledge gaps and future study directions are also highlighted.

4.1 Blockchain in smart buildings

Blockchain is an emerging concept in IoT based technology with strong links to smart buildings and smart cities. Blockchain has emerged as an important layer of trust (Siountri et al., 2020). as well as a novel approach for improving data integrity and privacy in smart buildings. Blockchain, a type of distributed ledger, can be utilized to reduce the challenges of information sharing and security in smart buildings (Rejeb et al., 2022). Unlike traditional databases, blockchain is built on a peer-to-peer network design in which all network users handle transactions effectively and flexibly rather than being controlled by a trusted centralized authority (Nguyen et al., 2020). It is conceivable to construct and update smart networks in the future, strengthen their resilience, and safeguard a rising amount and diversity of services by relying on blockchain's decentralization, immutability, and accountability. In this regard, blockchain has the potential to address important security concerns while also facilitating smart city operations (Rejeb et al., 2021). Machine learning is utilised to extract vital information from outsourced data and the findings are then stored securely on the blockchain to ease sharing (Rejeb et al., 2022).

The overall effect of blockchain and IoT can be improved with the introduction of 5G. Blockchain technology provides numerous answers to the issues posed by 5G networks. According to Azzaoui et al. (2020), the technology supports AI-powered 5G and leads to the development of a more efficient, and secure cellular network. As a result, 5G will serve as a foundation for IoT, blockchain and mobile edge computing (MEC), enhancing the analysis, collection and exploitation of smart building data (Hemmings, 2020) and making bandwidth less of a limiting factor in overall ecosystem design. With the transition to 5G networks, there is increased interest in investigating the pending issues of a 5G-enabled IoT for blockchain-based smart building applications, as 5G cellular networks are ineffective due to increasingly complex configuration issues in clouds and systems lacking AI functionality (Chen et al., 2020). As a result, future research should look at how blockchain might affect critical elements of IoT-based smart building applications (Rejeb et al., 2022).

4.2 AI in smart buildings

Artificial intelligence (AI) is another key area in IoT systems with strong links to smart buildings. The transition to smart buildings necessitates the collaboration of several technologies to make inhabitants' lives more convenient and inclusive (Ahad et al., 2020). AI is regarded as a critical tool for advancing urban sustainability and building more inclusive and secure settings, as supported by the United Nations' Sustainable Development Goal 11 (Sustainable development goal (SDG), 2015). AI systems rely on massive amounts of data and employ learning algorithms to discover patterns in the data, allowing for event prediction and decision-making tasks (Hariri et al., 2019). This is especially essential when combined with other developing technologies that increase efficiency by automating data collecting and eliminating the need for trusted third parties, hence maximizing profitability Hariri et al., 2019). In the work of Awan et al. (2020), for example, machine learning algorithms used to estimate parking spot availability in smart commercial buildings are thought to benefit from data collected by IoT sensors and devices.

Future research into this cluster may focus on how urban decision-makers might collaborate with residents to develop and create smart cities that meet their expectations. The subject of how to involve all stakeholders in a solution-oriented and citizen-centric manner while solving urban difficulties with IoT and AI approaches is of greater relevance (Brynskov, 2018). Empirical research is also required to better understand the stakeholder-related issues that enable or impede IoT and AI implementation in smart construction (Rejeb et al., 2022).

4.3 IoT for efficient energy management in buildings

Energy management is an empirical function of smart buildings with strong links IoT application to construction. The associated cluster describes how energy management in relation to IoT technology is gaining attention, with numerous sophisticated and ubiquitous smart construction applications, such as smart grids. Smart grids are modern power networks that can change and re-adjust dynamically to offer electricity at a cheap cost and high quality (Alsamhi et al., 2019). Since IoT applications consume a significant amount of energy, smart building solutions must be able to use energy more effectively and implement effective energy prediction systems that reflect the dynamics of the IoT environment (Luo et al., 2019).

The smart grid enables the exchange of energy and information between customers and utilities. Yet, the complexity of utilities to handling real-time data for making business-critical choices remains a difficulty (Alsamhi et al., 2019). Increased data usage improves grid stability and performance while also allowing the utility provider to make better decisions, allowing for efficient demand-side management and demand response. Nevertheless, the massive amount of raw data is incomprehensible or useless without a dependable and consistent capacity to process, analyse, and comprehend the information contained within such a massive amount of data. As a result, before taking action based on the data, the data must be turned into useable information. Such transformation is a difficult procedure since helpful information is not readily apparent from the data. Therefore, further investigation on the challenges faced by utilities to handle real-time data is essential (Syed et al., 2021).

4.4 Improved quality-of-service in smart buildings

Wireless sensor network (WSN) represents an important component of IoT by promoting resource efficiency and increasing smart inhabitants' quality of life (AlSawafi et al., 2020). WSN can handle large-scale installations in any metropolitan setting to perform tasks including real-time monitoring of physical and environmental conditions, routing and load balancing, industrial process monitoring, and energy efficiency optimization (Alsamhi et al., 2019). Researchers have previously focused on WSN-based smart building and city applications for scheduling and routing (e.g., smart grids) that take into consideration the energy efficiency and quality of service (QoS) (Faheem et al., 2019). Nonetheless, the mobility and changing network topologies of IoT nodes continue to pose challenges to the stringent fulfilment of QoS requirements in IoT-based smart building applications. As a result, future research must adapt current routing algorithms in WSN to give QoS guarantee in terms of latency, dependability, bandwidth usage, scalability, and throughput. Moreover, researchers must investigate low-cost methods of connecting IoT equipment and collecting data across the vast number of decentralised WSN in smart cities (Sobin, 2020).

4.5 IoT based sustainable construction design

Building energy efficiency is another key area with strong link to IoTs application to buildings. According to recent studies, tracking energy use in buildings has piqued the interest of many academics interested in IoT and energy saving measures (Xu et al., 2020). Furthermore, the drive towards combining smart buildings with cutting-edge detection techniques has begun to set the framework for seeing IoT as an essential component of smart cities (Al-Obaidi et al., 2022). Recent research has revealed a surge in interest in IoT applications in smart buildings to enhance energy efficiency and decrease environmental concerns. According to other research, if buildings consider effective communication between their systems for operation, they can save a significant amount of energy. As a result of advancements in networking, computing, and sensing technologies, IoT has emerged as a critical component in the design and operation of any smart item in the built (Kumar et al., 2022).

Smart design, smart action, smart control, smart monitoring, smart energy, smart waste and smart water are essential features of an IoT residential/commercial building that should be considered while converting a building to a smart one to make the atmosphere more comfortable not only for the residents but also for the management staff (Lawal & Rafsanjani, 2022).These features necessitate many types of data, and thus the key difficulty might be big data analytics, which arises from the huge, diversified, and time-evolving high-resolution data provided by IoT devices and sensors. The growth of technology has resulted in a dramatic increase in the number of connected IoT devices, resulting in massive data generation and transfer. To improve data flow between devices many different technologies are necessary, which raises the complexity of IoT systems in every kind and size of residential or commercial structure. Based on our analysis of the literature, smart waste and water have seldom been investigated and so additional future research into these aspects is advised to create a completely automated building (Lawal & Rafsanjani, 2022). Furthermore, IoT device batteries consume a large amount of energy and as a result, the rising rate of IoT device deployment has resulted in increased energy consumption making IoT and environmental concern which should be considered in future research (Lawal & Rafsanjani, 2022).

4.6 Buildings automation system

Building automation is yet another integral part of IoTs application to building with strong links to the research area. A building automation control system (BACS) is defined as a computer-based and automated system that analyses the specific needs of a building by controlling the associated mechanical and electrical plants/equipment installed in the building, thereby contributing to energy savings without compromising user thermal/visual comfort. A BACS's major goal is to maintain occupant thermal/visual comfort while maintaining an energy efficient and cost-effective building operation. It incorporates algorithms that replace user demands in directing technological systems depending on various objectives, such as; thermal comfort, Energy savings and cost savings (Gholamzadehmir et al., 2020).

The use of model predictive control, which also has a direct link to IoT application in buildings is a technique in BACS which has recently attracted a lot of interest from the scholarly community (Serale et al., 2018). An advanced control strategy (ACS) with a forecasting function, known as MPC, is necessary to achieve high energy and comfort performance levels by including renewable energy generation, innovative solutions for technical systems (e.g., heat pumps), and energy storage systems (Gholamzadehmir et al., 2020). MPC is commonly used in the building industry to forecast the dynamic behavior of systems in the future and alter reaction by the controller, accordingly, resulting in energy and cost savings while maintaining thermal comfort (Serale et al., 2018).

The evaluation of an accurate prediction horizon based on the system's characteristics is one of the fundamental concerns in predictive control systems (Gholamzadehmir et al., 2020). According to the literature study, the most typical setting for prediction and horizon control is one day ahead (Liu & Heiselberg, 2019). Nevertheless, the tuning of the prediction and control horizons may be influenced by the building boundary circumstances, such as the climate environment and building characteristics (Gholamzadehmir et al., 2020). There is particularly limited data on the link between the prediction horizon and control horizon. As a result, additional research is needed to analyse the relationship between prediction/control horizon and various building boundary conditions for best energy and cost saving outcomes. Because the predictive model is dependent on the quality of the input data, the function of sensor reliability and location are critical. There are just a few publications that report on this crucial issue and therefore research is required to fill this vacuum, which would otherwise be a weak spot for ACS (Gholamzadehmir et al., 2020).

Based on the study findings as discussed, predominant and emerging concepts that can serve as conduits for IoTs application in Buildings and the proposed directions for advancing research and practice are summarized in **Table 2**. Future investigations could pay more attention to the current and emerging concepts in IoT and its application to buildings.

Table 2: Themes, research area and future research direction

Theme	Research areas and concepts with links to IoT application in Buildings	Future research direction

Blockchain in IoT based smart buildings	Blockchain Privacy Smart city Security	Issues of a 5G-enabled IoT for blockchain-based smart building. applications Cost-effective and scalable blockchain solutions.
AI in smart buildings	Machine learning AI Sensors Activity recognition Ambient intelligence	Stakeholder-related issues that enable or impede IoT and AI implementation in smart buildings. How to involve all stakeholders in a solution-oriented and citizen-centric manner while solving urban difficulties with IoT and AI approaches
IoT for efficient energy management	Energy management Smart grid Micro grid Demand response Home energy management system	The complexity of utilities to handling real-time data for making business-critical choices
Improved quality-of-service in smart buildings	Wireless sensor networks Interoperability Neural network	Adapt current routing algorithms in WSN to give QoS guarantee in terms of latency, dependability, bandwidth usage, scalability, and throughput. low-cost methods of connecting IoT equipment and collecting data across the vast number of decentralised WSN in smart cities.
IoT based sustainable construction design	Building energy Efficiency Building Information Model Building envelope Green building Thermal energy storage Solar energy Sustainability	Investigation on smart waste and smart water Negative effects of IoT as an environmental concern
Building automation system	Building energy management system Anomaly detection	Analyse the relationship between prediction/control horizon and various building boundary conditions for best energy and cost saving outcomes

	Building automation Model predictive control Building control Hvac Indoor air quality thermal comfort	Reliability and proper location of IoT Sensors.

5. CONCLUSION

This study conducts a bibliometric review of the extant literature on IoT application in construction from 2008 to 2023 to tease out critical measures for its integration and transformation. In this study, 4875 publications on IoT within the building and construction sector retrieved from Scopus were analyzed using bibliometrics and network analysis in VOSviewer.

The demographic maturity levels and increased prevalence are most notably from China, Italy, the USA and UK Nevertheless, trends in recent IoT research are emerging from developing countries, indicating a surge for sustainable improvements in their construction practices. To enhance IoT research globally, developed and developing countries need to collaborate. The poor collaborative links between IoT researchers across developed and developing countries may be one of the reasons contributing to the slow understanding and uptake of IoT systems in developing economies. Therefore, funding research projects, research hubs and spoke networks and other collaborative research activities as appropriate between developed and developing countries should be highly encouraged. These can facilitate knowledge exchange and transfer on policies and implementation strategies to promote IoT application practice in construction.

Six cluster areas were identified including blockchain in smart buildings, IoT based sustainable construction design, Improved quality-of-service in smart buildings, building automation system, IoT for efficient energy management in buildings and AI in smart buildings. These areas currently seek to optimize energy efficiency in buildings, reduce waste and the environmental impact throughout a building's operation. There are emerging concepts from the cluster and there is the need to expound their links, especially block chain. This is with the view of foreseeing a more strategic approach for improving data integrity and privacy in smart buildings and cities.

This study contributed by highlighting the bibliometric research status of IoT in relation to its application in buildings, identified current gaps in the literature and provided directions for future studies and practice. More importantly, the evidence gleaned from this study would help IoT players and policymakers to develop bespoke strategies, frameworks and policy measures for integrating and implementing IoT practices, creating opportunities to transition to more sustainable systems in the construction sector. However, there were some limitations. One is the use of only Scopus database. Second is the use of only Journal articles and reviews written in English, and third is the exclusion of discussions of other emerging areas because they had no current links to IoT. Future research may use other databases or incorporate data from different sources to enhance generalizability. They can also broaden the sources of documents such as books and include those in foreign languages, to broaden the variety of data. Future research might investigate additional growing sectors where there are presently no linkages to IoT. In addition, expert systems and fuzzy tools can be used to explore a more in-depth quantitative analysis.

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CARBON TRACKING IN THE BUILDING SECTOR: A 'CABBAGE' FRAMEWORK

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ABSTRACT: *The great challenge of global climate change urges world economies to reduce greenhouse gas emissions and promote sustainable development, where the building sector plays a vital role. Carbon tracking technology is one of the keys to capturing carbon emissions for sustainable construction such as net-zero buildings. This paper reviews five key carbon tracking technologies – life cycle assessment (LCA), energy modeling, building operation monitoring, carbon accounting software, and green certification and rating systems. With summarized advantages, beneficiaries, and limitations of the five technologies, we propose a Carbon Tracking 'Cabbage' (CTC) framework that incorporates all carbon tracking tools as inner technological layers for multiple stakeholders at multiple stages of construction management. The main contribution of this paper is the CTC framework that rationalizes the scopes and adoption strategies of carbon tracking technologies by collaborative stakeholders to achieve informed decision-making, implement effective carbon reduction strategies, and subsequently contribute to climate change mitigation actively.*

KEYWORDS: *Carbon tracking; Building sector; Carbon tracking cabbage framework; multi-stakeholder; Technology adoption*

1. INTRODUCTION

Global climate change poses an increasingly severe challenge to human society and ecosystem. Carbon emissions, as a major source of greenhouse gases, have been widely recognized as one of the primary drivers of climate change. In light of this, establishing a sustainable green economy through collective global efforts has become a pressing priority. The building sector plays a crucial role in global carbon emissions, accounting for a significant portion of the global greenhouse gas output (Khalili & Chua, 2013). As society strives to combat climate change and become carbon neutral, addressing the carbon footprints of buildings and adopting sustainable practices in the construction and operation of these structures has become a top priority.

Tracking and monitoring carbon emissions, particularly carbon dioxide (CO_2), reveal evidence and insights into the amount of carbon in the atmosphere, enabling targeted strategies to reduce emissions and mitigate the impacts of climate change (Liu et al., 2020). Carbon tracking, as an essential component of the broader carbon management strategy, has emerged as a powerful tool to measure, monitor, and mitigate the carbon impact of buildings (Liu et al., 2020). Additionally, carbon tracking provides crucial data for setting emission reduction goals, empowering governments, organizations, and industries to establish clear and achievable targets while monitoring progress. Through carbon tracking and reporting, businesses can measure the carbon footprint, identify improvement opportunities, transparently disclose environmental impacts to stakeholders, and showcase the social responsibility. Furthermore, standardized carbon tracking and reporting methods foster global cooperation, which enables international transparency, peer pressure, and collaboration in achieving shared climate goals (Kang et al., 2015). In summary, carbon tracking and reporting are essential tools in combating climate change, providing vital data to empower decision-makers, businesses, and individuals to take proactive action in creating a more sustainable and resilient future.

The significance of carbon tracking technologies in the building sector lies in measurability and interpretable evidence of comprehensive carbon emissions across the entire lifecycle of a building. From the production and transportation of construction materials to energy consumption during building operations and eventual demolition, these technologies offer valuable insights into the carbon impact of each stage, enabling informed decision-making and targeted carbon reduction strategies. Over the years, carbon tracking technologies in the building sector have undergone significant advancements and innovations (Xu et al., 2023). From traditional methodologies to cutting-

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Jiajia Wang, Geoffrey Qiping Shen, Fan Xue, *Carbon Tracking in the Building Sector: A 'CABBAGE' Framework*, pp. 1085-1093, DOI 10.36253/979-12-215-0289-3.108

edge digital solutions, these tools have played a pivotal role in quantifying the carbon footprint of buildings at different stages of their lifecycle. By providing a holistic assessment of carbon emissions, these technologies empower stakeholders, including architects, engineers, policymakers, and building owners, to make informed decisions that foster sustainable building practices.

However, current carbon tracking technologies fall short of encompassing the entire building lifecycle in the building sector. Although individual technology is advantageous, carbon tracking as a whole is always fragmented and incomplete. Subsequently, the fragmented and incomplete carbon tracking hinders holistic and effective carbon reduction strategies and leads to missed opportunities for emission mitigation and sustainable practices. Thus, there is a significant research gap in a comprehensive approach that spans carbon tracking to all stages of a building's lifecycle.

This paper embarks on a novel framework that rationalizes the full-lifecycle carbon tracking based on an in-depth exploration of all the carbon tracking technologies in the building sector. By reviewing historical milestones, technological breakthroughs, and real-world applications, we aim to present a comprehensive overview of the evolution of these technologies and their impact on the industry's sustainability efforts. The primary objectives of this study are:

- To provide an in-depth analysis of the historical evolution of carbon tracking technologies in the building sector, highlighting key milestones and breakthroughs that have shaped their current state;
- To examine the existing carbon tracking technology models, methodologies, and tools deployed in the building industry, assessing their effectiveness, limitations, and potential for future enhancements; and
- To explore real-world case studies and successful implementations of carbon tracking strategies, showcasing how these technologies have contributed to carbon reduction goals and sustainable building practices.

2. LITERATURE REVIEW

2.1 Existing carbon tracking technologies

As shown in Fig. 1, there are five main categories of carbon tracking techniques. They are LCA, energy modeling, building operation monitoring, carbon accounting software, and green certifications and rating systems. The associated phases and key technologies are sketched along the of a curved arrow of a typical construction project course in Fig. 1.

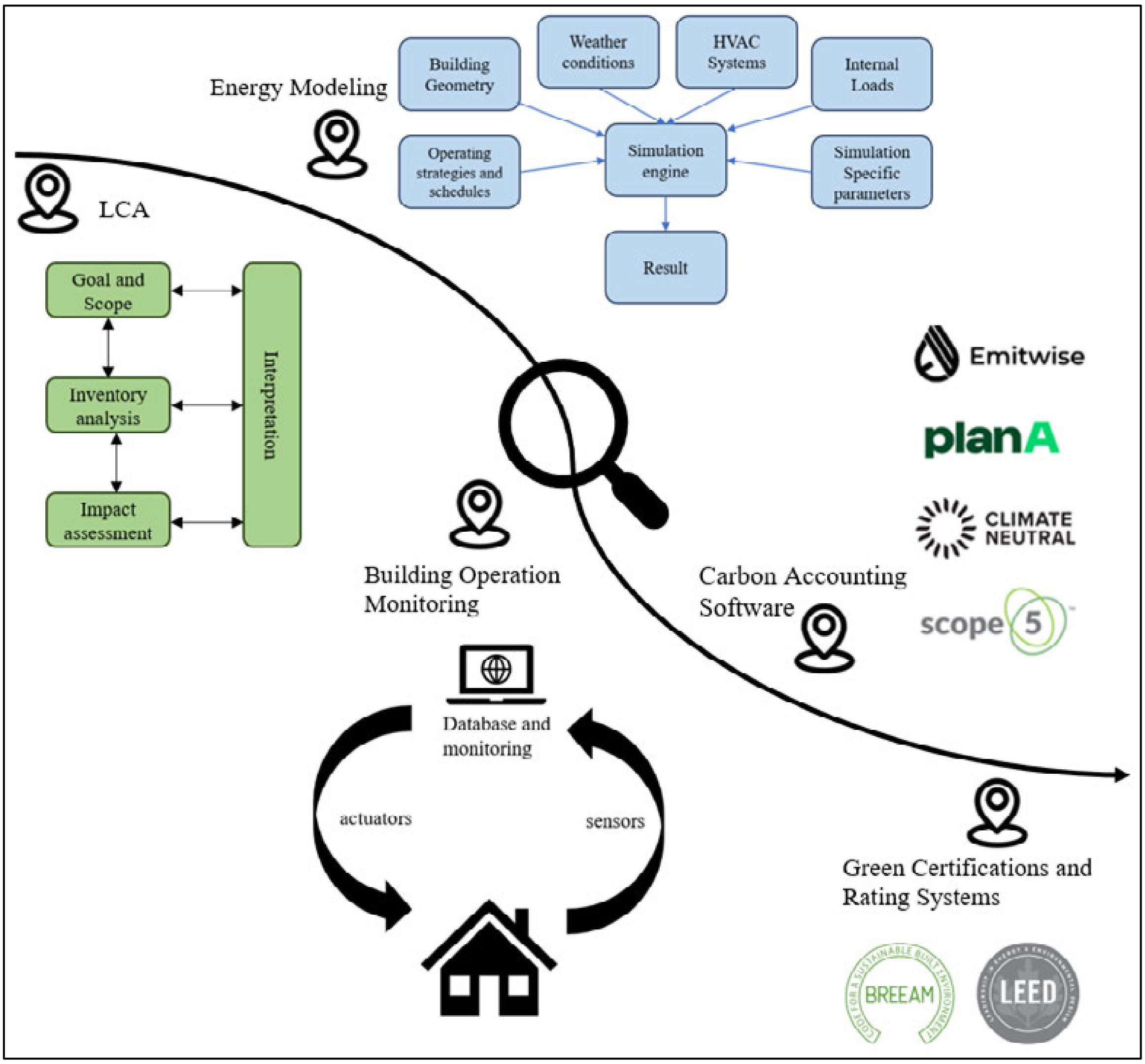

Fig. 1: Conceptual map of existing carbon tracking technologies.

LCA. LCA is a systematic method used to assess the carbon emissions generated throughout the entire lifecycle of a building, including raw material procurement, construction, operation, and demolition (Dodoo et al., 2014). By comprehensively regarding the environmental impacts at each stage, LCA provides comprehensive carbon emission data, guiding design and material selection to achieve sustainable and low-carbon building solutions. The strength of LCA lies in its comprehensiveness, such as material production, transportation, construction, and dismantling, beyond the building's use phase. Thus, LCA offers a more holistic evaluation of the building's environmental impact.

Energy Modeling. Energy modeling is a method that involves simulating a building's energy consumption using specialized software, thereby estimating carbon emissions. These models integrate factors such as building design, energy systems, and climate conditions, providing architects and energy experts with optimized strategies to enhance energy efficiency and reduce carbon emissions (Wang et al., 2021). Energy modeling allows decision-makers to predict a building's energy performance under different conditions during the design phase, facilitating environmentally friendly and energy-efficient choices. Additionally, it enables continuous monitoring and optimization of energy usage during the subsequent operational phase.

Building Operation Monitoring. Building operation monitoring entails the installation of sensors and monitoring systems to collect real-time data on energy consumption and emissions. These monitoring systems help building managers gain better insights into energy usage, promptly identify potential energy waste, and implement measures to reduce carbon emissions (Bilec et al., 2010). Continuous monitoring enables building managers to track energy performance and make timely adjustments and improvements to achieve sustained carbon reduction.

Carbon accounting software. Carbon accounting software is a specialized tool used to track and record carbon emission data for building projects and companies. These software solutions typically offer data collection, analysis, and reporting functionalities, facilitating the formulation of carbon reduction strategies and supporting the realization of carbon neutrality and emission reduction goals (Liu et al., 2019). Carbon accounting software empowers the building industry to efficiently collect and manage carbon emission data, providing support for achieving carbon neutrality and emission reduction objectives.

Green certifications and rating systems. Some countries and regions have introduced green building certification and rating systems, such as LEED, BREEAM, and Green Building Labels. These systems comprehensively assess a building's environmental performance, including carbon emissions, thus encouraging the adoption of more environmentally friendly design and operational practices in the construction industry. Participation in green certifications and ratings allows building projects to gain recognized environmental recognition, enhance market competitiveness, and contribute to sustainable development (Wang, Teng, et al., 2021). These green certification systems provide a clear goal for the building industry, driving the sector towards a more environmentally friendly and low-carbon direction (Chang et al., 2016). By comprehensively applying these carbon tracking technologies and practices, the building industry can play a proactive role in addressing global climate change and collectively create a more sustainable and greener future.

2.2 Advantages, beneficiaries and limitations of carbon tracking

This subsection provides an in-depth examination of the advantages and limitations of different carbon tracking technologies used in the building sector. The technologies discussed include LCA, Energy Modeling, Building Operation Monitoring, Carbon Accounting Software, and Green Certifications and Rating Systems. Each technology's advantages and limitations are summarized for comparison. The beneficiaries are also analyzed to gain a comprehensive understanding of the benefits in sustainable and low-carbon building practices.

Table 1: Advantages, beneficiaries, and limitations of carbon tracking technologies.

Carbon tracking tech.	Advantages	Beneficiaries	Limitations
LCA	• Comprehensive and holistic approach • Enables optimized design and material selection	• Building owners and developers • Government agencies and regulatory authorities • Environmental organizations and NGOs	• Data-intensive and time-consuming • Dependent on data quality and availability
Energy Modeling	• Virtual simulations for energy efficiency • Allows iterative design improvements	• Architects and engineers • Energy managers	• Relies on input assumptions and model accuracy • Real-world performance may differ from predictions
Building Operation Monitoring	• Provides real-time data on energy consumption • Identifies energy wastage and reduction potential	• Building owners and developers • Energy managers	• Requires infrastructure of sensors and data systems • Interpretation may need specialized expertise
Carbon Accounting Software	• Streamlines data collection and analysis • Supports progress tracking and mitigation strategies	• Building owners and developers • Government agencies and regulatory authorities	• Choosing appropriate software can be challenging • Reliability depends on data accuracy and completeness
Green Certifications and Rating Systems	• Offers standardized benchmarks for sustainability • Incentivizes eco-friendly design and practices	• Building owners and developers • Environmental organizations and NGOs	• Time-consuming and resource-intensive certification • Potential gap between predicted and realized outcomes

LCA's strength lies in the comprehensive assessment capability, which takes into account the environmental impact of the life cycle stages of the building. LCA provides comprehensive carbon emission data and other environmental indicators and helps decision makers to fully understand the environmental performance of the building. Through LCA, builders can compare the environmental performances of different design and material options to make more informed choices, optimize building design and material choices, reduce carbon emissions and environmental impact, and achieve sustainability goals (Hong et al., 2015). However, LCA also has some challenges and drawbacks. Its complexity is a significant problem. The implementation of LCA is complex and costly, because it requires a large amount of data collection, analysis and calculation, and has high technical and professional requirements. In addition, the reliability of LCA depends on the quality of the data and the reliability of data source. Therefore, incomplete or missing data can lead to uncertainty in the results and misled decisions. At the same time, conducting LCA also requires a significant investment of time and resources, which may become impractical or difficult to apply to complex construction projects.

Energy modeling can provide architects and energy experts with comprehensive data and information to gain insights into a building's energy use. With the simulation results of a building's energy consumption under different conditions, decision makers can predict a building's energy performance and make environmentally friendly and energy efficient decisions at the early design stage. Secondly, energy modeling integrates factors such as building design, energy system and climate conditions to provide solutions for building projects to optimize energy efficiency and reduce carbon emissions. Therefore, energy modeling can reduce energy costs and environmental impact throughout the life cycle (Li & Chen, 2017). However, energy modeling's reliability depends on the accuracies of both input data and the building model. Inaccurate data or modeling can lead to biased results and ineffective decisions. Secondly, energy modeling requires a high level of technology and expertise, and there may be barriers to learning and application for some builders. In addition, energy modeling also requires a certain amount of time and resource investment, especially for complex construction projects, which may increase the difficulty and cost of implementation.

Building operations monitoring provides real-time and accurate energy consumption data to help building managers get a complete picture of a building's energy use. Through continuous monitoring, managers can immediately grasp the energy consumption of the building, find potential energy waste and problems in time, and provide a basis for taking targeted measures. Secondly, operational monitoring can help optimize a building's energy use and operational strategies to achieve ongoing carbon reduction and energy conservation goals. By aligning operations with actual data, builders can reduce carbon emissions and energy costs and improve operational efficiency (Geng et al., 2022). However, the installation and maintenance of building monitoring systems may require certain inputs and costs. The selection, installation and commissioning of sensors and monitoring equipment require specialized technical support. Secondly, the processing and analysis of large amounts of real-time data may also require certain technical and management capabilities (Geng et al., 2022). For some builders, it may be necessary to train and improve the data analysis and operations management skills of relevant personnel. In addition, the building monitoring system also faces the problem of data security and privacy protection, and it is necessary to establish a reasonable data management and protection mechanism to ensure data security and compliance.

Carbon accounting software enables efficient data collection and management. By automating data acquisition and processing, manual operation and time cost can be greatly reduced, and the accuracy and reliability of data can be improved. Secondly, carbon accounting software provides powerful data analysis and reporting capabilities, capable of turning complex carbon emissions data into intuitive charts and reports to provide clear insight and guidance for decision-makers (Long et al., 2018). This helps to develop carbon reduction strategies and track progress, driving the construction industry in a lower carbon direction. However, choosing the right carbon accounting software for your needs requires consideration of a number of factors, including the software's functionality, compatibility, price, and user-friendliness. Different software may be suitable for different sizes and types of construction projects, so careful evaluation and selection are required. Secondly, it is necessary to ensure the accuracy and integrity of the data during the use of the software, otherwise, it may lead to errors and inaccurate analysis of the results. Therefore, the construction industry needs to establish a reasonable data collection and verification mechanism to ensure that the software output data is reliable and usable.

The Green certification and rating system provides the construction industry with clear environmental standards and targets, driving the construction industry to adopt more environmentally friendly and sustainable design and operation practices. By participating in certification and rating, construction projects can receive recognized environmental recognition, improve their market competitiveness, and attract more environmentally conscious customers and investors. Secondly, the green certification and rating system takes into account the environmental performance of the building, including carbon emissions, energy efficiency, material use and indoor environmental quality, so as to achieve comprehensive environmental benefits and sustainable development (Ma et al., 2020).

However, some rating systems may be too complex and cumbersome, requiring large amounts of data and proof to meet certification standards, increasing costs and burdens for builders. Secondly, the certification and rating process can be time-consuming, affecting the schedule and operation of the project. In addition, sometimes the rating results may only reflect the design and planning stages of the building and do not actually take into account the actual operation and use of the building, and therefore may be biased from the actual environmental performance.

3. THE PROPOSED CARBON TRACKING 'CABBAGE' FRAMEWORK

Fig. 2 presents the proposed Carbon Tracking 'Cabbage' (CTC) framework. The architecture of CTC framework represents the characteristics and beneficiaries of all the five technologies. The integrated framework can enable builders and all stakeholders to get a comprehensive picture of the carbon emissions of buildings. The quantitative carbon tracking results also enables carbon reduction strategies and plans in a data-driven manner, driving the construction industry towards a greener and low-carbon direction in the digital era. Incorporating a multi-stakeholder engagement approach, the CTC framework fosters collaboration among diverse participants, including architects, engineers, policymakers, and environmental experts, creating a synergistic effort to address carbon emissions and advance sustainability within the construction industry. With integrated carbon tracking technologies and evidenced-based multi-stakeholder practices, the construction industry can play an active role in contributing to the global response to climate change and co-creating a more sustainable and green future.

Fig. 2: The proposed Carbon Tracking 'Cabbage' framework in this paper.

3.1 Rationale

Carbon tracking and management becomes distinctly robust and strategic based on the CTC framework. This comprehensive approach stems from the imperative to synergize diverse data streams, resulting in a panoramic understanding of an organization's carbon footprint and the cultivation of a holistic strategy for sustainable practices. By seamlessly integrating techniques like LCA, Energy Modeling, Building Operation Monitoring, Carbon Accounting Software, and Green Certifications and Rating Systems, stakeholders attain a multifaceted perspective on their carbon emissions, uncovering insights that span the entire spectrum of product lifecycles.

Energy modeling serves as a vital supplement to this perspective, shedding light on emissions linked to energy usage, while real-time operational data from building operation monitoring introduces an agile layer of information. Carbon accounting software meticulously quantifies emissions, and green certifications provide benchmarks for measuring sustainability performance. The true power of integration lies in its ability to provide a nuanced analysis of emissions' sources and potential reduction avenues. This comprehensive comprehension empowers organizations to precisely identify processes or lifecycle stages that contribute significantly to the carbon footprint, facilitating the strategic alignment of reduction efforts with broader sustainability objectives.

Furthermore, the incorporation of real-time monitoring and reporting, seamlessly facilitated by building operation monitoring and carbon accounting software, bestows organizations with the nimbleness to make swift, well-informed decisions. The trajectory towards carbon reduction objectives can be closely monitored, enabling agile adjustments in real-time that optimize the efficiency of sustainability initiatives. The integration of esteemed green certifications and rating systems augments the credibility of these endeavors, ingraining transparency and accountability within the organizational approach to sustainability. In essence, this fusion of techniques underscores a sagacious and pragmatic approach to surmounting the intricate challenges of carbon reduction, laying the essential groundwork for a verdant and more sustainable future, fortified by data-driven insights and strategic harmony.

3.2 Adoption strategies

The CTC framework provides actionable strategies for stakeholders to adopt in order to achieve their carbon reduction goals. By facilitating data integration and collaboration across departments, organizations can ensure a seamless flow of information from technologies such as LCA, energy modeling, building operations monitoring, carbon accounting, and green certification. This collaborative approach promotes a comprehensive understanding of carbon emissions, enabling informed decision-making and targeted mitigation efforts. The implementation of advanced technology solutions has become a key strategy. By investing in carbon accounting software, energy management systems, and IoT devices for real-time monitoring of building operations, organizations can improve their ability to accurately quantify emissions and optimize energy use in a timely manner. A continuous improvement cycle is essential, where real-time monitoring data informs regular review and analysis to identify trends and areas for improvement. Over time, this iterative process enhances carbon reduction strategies and optimizes operations.

Transparently communicating efforts to reduce carbon emissions to stakeholders demonstrates a commitment to sustainability, while incentive programs and recognition boost employee motivation and morale. Long-term strategic planning ensures that organizations remain adaptable and resilient in their carbon reduction initiatives. Overall, the CTC framework serves as the foundation for implementing these strategies, guiding organizations toward a more sustainable and environmentally responsible future.

3.3 Application scenarios of the CTC framework

The CTC framework can guide sustainable construction management in different phases of a construction. For example, the framework integrates LCA and energy modeling, enabling design teams to assess the environmental impact of different design options. This enables the selection of materials, systems and technologies that meet carbon reduction targets, creating a solid foundation for sustainable projects. As the construction phase begins, the CTC framework maintains its importance. The integration of real-time monitoring and data-driven insights gives construction teams the means to track energy consumption and emissions in real time. During construction, rapid interventions can be implemented to optimize energy use and reduce carbon emissions, reflecting the immediate utility of the framework.

During the operational phase, the framework facilitates continuous monitoring and ensures the continuous and efficient operation of construction projects. Building operation monitoring ensures sustainable performance, while carbon accounting software tracks ongoing emissions. In addition, a recognized green certification and rating system is used to validate and communicate the sustainable achievements of the project to stakeholders, promoting transparency and accountability. Finally, during the retrofit and retrofit phases, the CTC framework guides informed decision-making by assessing the carbon emissions impact of retrofit choices. By seamlessly integrating LCA and energy modeling, retrofit teams can strategically upgrade systems, materials, and technologies to achieve the best carbon reduction outcomes.

All in all, the CTC framework serves as a comprehensive and adaptable tool for effective and sustainable construction management at all stages of a construction project. By leveraging its integrated technology, stakeholders are able to make informed, data-driven decisions that align with carbon reduction targets, advance environmentally responsible building practices, and contribute to a greener future.

4. DISCUSSION

As carbon emissions continue to be the primary driver of climate change, tracking and mitigating carbon emissions has become a top priority for governments, organizations and industries around the world. The construction sector's significant contribution to global carbon emissions underscores the need to focus on reducing the carbon footprint of buildings throughout their life cycle. Carbon tracking becomes a powerful tool for measuring, monitoring and mitigating the carbon impact of buildings. By tracking and monitoring carbon emissions, policymakers gain valuable insights into the amount of carbon in the atmosphere, enabling targeted mitigation and climate change strategies. Carbon tracking also helps to set clear and achievable emission reduction targets and promotes global cooperation and transparency to achieve common climate goals.

In addition, it is important to standardize carbon tracking and reporting methods to ensure consistency and comparability in international Settings. These technologies enable businesses to measure their carbon footprint, identify opportunities for improvement, and demonstrate to stakeholders their commitment to environmental responsibility. In the construction sector, carbon tracking technology provides a comprehensive understanding of the carbon emissions of buildings throughout their life cycle. From construction through operation to final demolition, these tools provide insights for informed decision-making and promoting sustainable building practices. Throughout the inquiry, the focus remained on the development and advancement of carbon tracking technology. From traditional methods to cutting-edge digital solutions, these technologies continue to improve our ability to quantify and understand carbon emissions, making them indispensable in our fight against climate change.

Overall, carbon tracking technologies enable stakeholders to make informed choices, assess the environmental impact of their actions, and work together to build a more sustainable and resilient future. By providing valuable data and insights, these technologies are transforming the construction industry and moving us closer to a carbon-neutral and healthier planet.

5. CONCLUSION

In summary, this comprehensive review highlights the significance of carbon tracking technologies in the building sector for combating climate change and promoting sustainable practices. The five key technologies—LCA, Energy Modeling, Building Operation Monitoring, Carbon Accounting Software, and Green Certifications and Rating Systems—each play essential roles in understanding, monitoring, and reducing carbon emissions in buildings. LCA provides a comprehensive view of a building's carbon footprint across its entire life cycle, guiding sustainable design and material choices. Energy Modeling allows for energy consumption simulation and optimization during the operational phase, enabling the early implementation of energy-efficient strategies. Building Operation Monitoring offers real-time data collection to understand and reduce energy wastage. Carbon Accounting Software tracks emissions and sets reduction goals, while Green Certifications and Rating Systems incentivize sustainable practices.

A proposed Carbon Tracking 'Cabbage' (CTC) framework integrates all the technologies and empowered stakeholders for data-driven decision-making, carbon reduction strategies, and sustainability initiatives. Collaboration among researchers, policymakers, and industry professionals, as sketched in the CTC framework, is crucial for implementing this framework and achieving a greener and more sustainable future. By embracing carbon tracking technologies under the CTC framework, the building sector can actively contribute to mitigating climate change and creating a resilient and environmentally responsible world.

However, the CTC framework in this paper is conceptual. We require a system platform and pilots in the industry to realize and validate the effectiveness of the CTC framework. Furthermore, the arguments and discussion only flows at the surface of general cases. Fine adjustments are necessary for each construction 'niche' industry to meet construction industrial standards, supply chains, and cultures for carbon tracking of the whole life cycles of buildings.

ACKNOWLEDGEMENT

The work presented in this paper was supported by the Hong Kong Research Grants Council (RGC) (Nos. C7080-22GF, 15225822).

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RETROFITTING OF BUILDINGS TO IMPROVE ENERGY EFFICIENCY: A COMPREHENSIVE SYSTEMATIC LITERATURE REVIEW AND FUTURE RESEARCH DIRECTIONS

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ABSTRACT: *A large body of research has been developed with the aim of assisting policymakers in setting ambitious and achievable environmental targets for the retrofit of current and future building types for energy-efficiency and in creating effective retrofit strategies to meet these targets. The aim of this research is to conduct a comprehensive study to identify the relationship between building type and sustainability, with a particular emphasis on retrofitting and try to identify research gaps in the most effective energy-saving strategies for retrofitting various types of buildings. In this regard, this study conducts a systematic literature review (SLR) utilizes artificial intelligence (AI) and natural language processing (NLP). Sixty relevant papers are selected and reviewed, establishing a comprehensive searching scheme. The research highlights retrofitting strategies for improving energy efficiency in buildings and discuss the limitations of current practises in terms of physical and technical developments, such as utilising new energy systems and innovative retrofitting materials. To overcome these, future studies could focus on in-depth building classification, developing tailored retrofitting alternatives, and establishing an adaptive solution framework. This framework aligns cohesively with diverse typologies, adapting to changing contexts and enhancing long-term performance.*

KEYWORDS: *retrofitting, typology of building, building energy performance, residential buildings.*

1. INTRODUCTION

Buildings account for 40% of the overall energy consumption in the European Union (Ballarini et al., 2017). Improving building energy efficiency is currently considering a top priority by the UK government as a major initiative for accelerating the decarbonization agenda for the building industry by 2050. European policy aims to achieve a 27% increase in energy efficiency by 2030, primarily by improving the energy efficiency of newly constructed buildings. However, the number of new buildings is small compared to the total stock of buildings in Europe, accounting for only 1%. Therefore, the most crucial aspect of energy-saving in Europe is retrofitting of existing residential buildings (Pungercar et al., 2021). Nevertheless, according to (Ortiz et al., 2020), the UK government's main barrier in this regard, tends to be reducing carbon emissions from existing residences. To improve the long-term energy performance of the building stocks and reduce carbon emissions, governments should develop a strategy to invest in building energy refurbishment(Ballarini et al., 2017). A large body of research has been developed to assist policymakers in setting ambitious and achievable environmental targets for converting a certain building type to energy-efficient structures and creating effective strategies to meet these targets (Re Cecconi et al., 2022). However, building regulations are frequently changed, depending on each country's vision, potential, capacity to implement such changes, and the complexity of architectural details and conditions within its building stock (Alabid et al., 2022).

Several variables play a pivotal role in shaping energy consumption within a building, including the building envelope's structure, age distribution among existing building stocks, prevailing climate conditions, building area and type, the building's age, and the efficiency of its system installations (Beagon et al., 2020). In order to promote local or national energy-saving strategies, typical residential building typologies are commonly used to model the energy efficiency of building portfolios (Loga et al., 2016).

Indeed, one crucial aspect that contributes to the complexity of retrofitting residential buildings lies in the fact that each building's characteristics can significantly vary based on the environmental conditions of its location. While previous research, as highlighted by (Kadrić, Aganovic, Martinović, et al., 2022), has delved into the challenges and opportunities of retrofitting different building types, there remains a notable gap in the literature concerning the explicit consideration of environmental factors during the retrofitting process. This research aims to address knowledge gaps by utilizing a novel searching framework that employs an AI algorithm. It seeks to analyse the existing literature concerning the correlation between building types and energy-efficient retrofitting, including the influence of environmental factors on energy-saving strategies according to building's typology. The goal is to identify crucial areas for future research and enhance the understanding of the relationship between building

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Elena Imani, Huda Dawood, Nashwan Dawood, Annalisa Occhipinti, *Retrofitting of Buildings to Improve Energy Efficiency: A Comprehensive Systematic Literature Review and Future Research Directions,* pp. 1094-1104, DOI 10.36253/979-12-215-0289-3.109

typology, energy efficiency, and retrofitting.

2. RESEACH METHODOLOGY

Highlighting the most recent developments in many areas of research is essential to ensuring progress and innovation in those areas. However, with an overwhelming number of publications, it becomes challenging to thoroughly read and analyze each one. Ignoring them entirely is not a viable option either, as valuable insights might be missed. Therefore, there is a pressing need to develop a new search scheme that effectively filters publications, ensuring a comprehensive review without overlooking significant contributions. The methodology employed in this research involves a multi-step approach to ensure a comprehensive and robust review of relevant studies (Figure 1).

The research begins by conducting a SLR proceess and develop an algorithmic gap spotting framework, which serves as a fundamental aspect of the process. This framework encompasses the formulation of effective search strategies and the establishment of stringent study selection criteria. By implementing this approach, the research aims to identify and address gaps in existing literature, enhancing the overall quality of the review. Following the development of the framework, the quality of the studies included in the review is thoroughly evaluated. This evaluation focuses on determining the probability of bias and assessing the reliability of the supporting data. By conducting this assessment, the research ensures that only high-quality studies are considered in the analysis, enhancing the credibility and validity of the findings. Based on the results obtained from the algorithmic gap spotting framework and study evaluation, this research aims to identify gaps in the existing literature and design future study. These gaps indicate areas where further investigation is needed to address unanswered questions or explore novel perspectives. By identifying these research gaps, the study aims to contribute to the advancement of knowledge in the field.

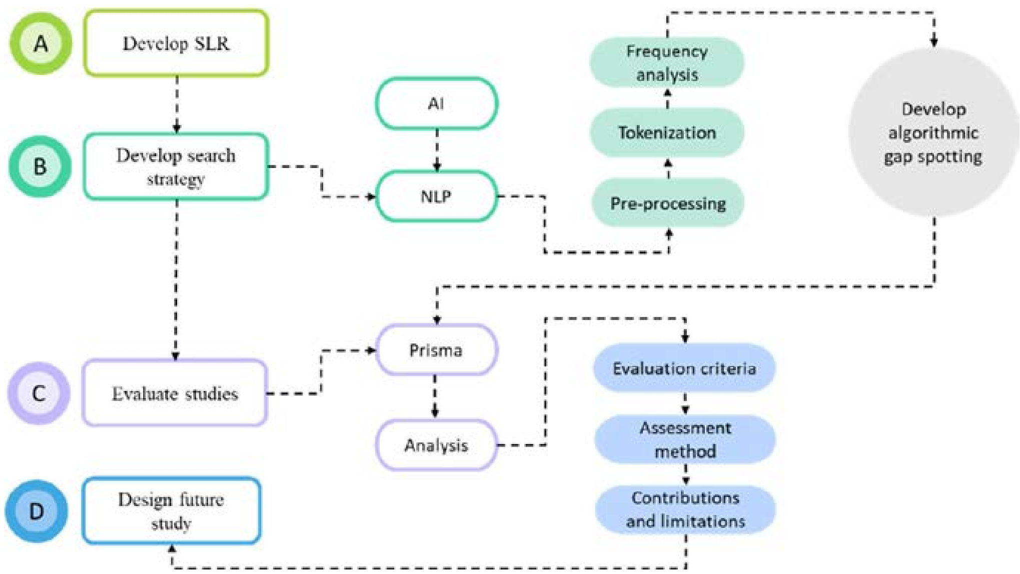

Fig. 1: Research methodology

2.1 Systematic literature review

To fully address a research topic, this study used (SLR) technique. The methodology employed in this publication for conducting (SLR) involves two main steps for defining keywords. Firstly, database selection was performed, and subsequently, a search strategy was developed. This process resulted in the identification of 402 relevant publications that were then selected for evaluation and analysis. The systematic literature review (SLR) process identified 60 relevant papers using PRISMA methodology (Figure 2). This approach provided valuable insights into energy efficiency, particularly building typology's role, crucial for decision-makers and designers.

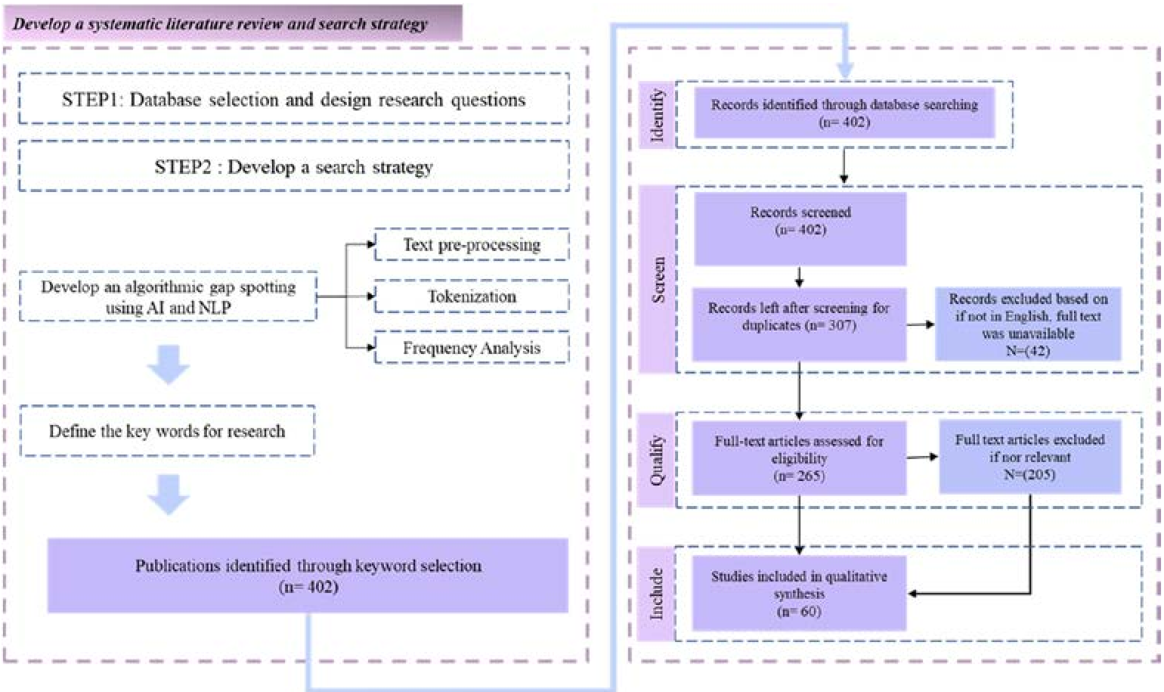

Fig. 2: Search strategy framework

2.2 Algorithmic gap spotting

The research questions addressed in this section are:

RQ1. How much publications have there been about relationship between building type and energy efficiency through retrofitting since 2011?

RQ2. What are the limitations of current research in this area?

In order to answer the research questions, this study reviewed literature related to construction building technology, civil engineering, green sustainable science technology and environmental science fields to catch the most relevant articles. This study introduces a novel approach to addressing the challenge of search strategy for identifying research gaps in existing literature. By leveraging AI algorithms, NLP techniques, and data analysis, a strategy called algorithmic gap spotting (algorithmic gap roadmap) is employed. This method offers an automated and systematic way to identify areas of research or knowledge where there are gaps, enabling researchers to guide future studies, recognize biases and limitations, and foster innovation in various fields (Figure 3).

Algorithmic gap spotting involves the utilization of computational tools to analyse and interpret large volumes of published research papers, articles, and other relevant documents. By applying AI algorithms and NLP techniques, patterns and trends within the data can be identified, such as keyword frequency, co-occurrence of terms, and the distribution of topics across different domains.

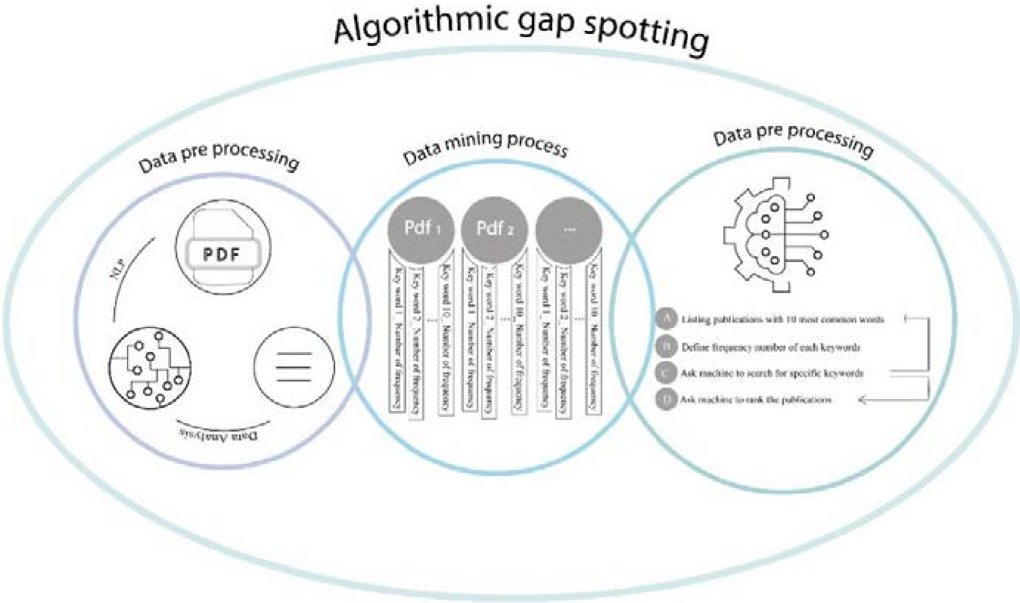

Fig.3: Algorithmic gap spotting design process

3. RESEARCH FINDINGS AND REVIEW RESULTS

As mentioned before, building retrofitting is an effective approach to reducing energy consumption and carbon emissions. However, it is a complex process that requires consideration of various factors. Despite its potential benefits, there is still a lack of information on factors that impact retrofitting solutions. This research aims to address these gaps by conducting a comprehensive literature survey. Reviewed publications in the previous section identified two main areas that remain a gap in the literature, which are building retrofit assessment according to the typology of building and building retrofit assessment according to environmental factors. This paper discusses the importance of addressing these gaps and presents recommendations for future research in these areas.

3.1 Building retrofit assessment according to the typology of building

Building typologies play an essential role in achieving energy performance requirements of buildings. By considering building typologies, a comprehensive understanding of a building stock's energy efficiency can be gained, making it an indispensable tool in ensuring sustainable and energy-efficient buildings (Y. Li et al., 2019).

Numerous pieces of evidence have been identified through the analysis of architectural typologies related to energy in the European Union, at both national and regional levels. Typological data and criteria are being used to develop informational materials and provide energy advice for buildings (Dascalaki et al., 2011a). Moreover, typical residential building typologies are also being employed as tools for modelling the energy efficiency of building portfolios to promote local or national energy-saving strategies (Ballarini et al., 2011a). The main purpose of building typology is to determine the best energy-efficiency techniques to implement in existing structures and quantify the potential energy savings and $CO2$ emission reductions associated with the implementation of energy refurbishment measures in the building stock at various scales (Fernandez-Luzuriaga et al., 2021).

According to (Sugár et al., 2020), building typology also plays a crucial role in determining a building's energy consumption. For instance, the heating energy demand of a building depends on its architectural style, and typology can be used to calculate a building's heating energy requirement. The main objective of this research is to present a study through literature related to the connection between sustainable retrofitting and building typology. The process systematic search method for retrofit decision-making intends to provide thought-provoking insights into the shortcomings and outlines the most important directions for future research.

3.2 Building retrofit assessment according to Environmental factors

The influence of the surrounding environment on building heating energy consumption has been recognized as a critical factor in addition to the physical condition of a building. While the latter factors have been extensively studied, (Song et al., 2020) highlights the importance of urban morphology and climatic conditions in determining the overall heating demand in buildings. There are various global environmental assessment schemes that evaluate the impact of projects on different factors related to sustainability (Del Rosario et al., 2021). This section tries to investigate and comprehend the environmental aspects that influence the energy efficiency of buildings. It highlights a requisite for additional research to advance more precise and comprehensive assessment frameworks that encompass the environmental sustainability of retrofitting strategies.

3.2.1 Building retrofit assessment according to the climate conditions

The classification of buildings varies depending on the climate condition of the region and retrofitting strategies must be tailored to specific climate conditions and building types to ensure their effectiveness (Boardman, 2007). The primary aim of building typology is to create structures that are responsive to their environment while maximizing the use of resources available (Kirkegaard & Foged, 2011) (Tompkins & Adger, 2003). Retrofitting strategies towards energy-efficient buildings in specific climate conditions may have a common target; however, they differ in their strategies. Numerous studies conducted in various locations highlight retrofitting solutions tailored to their specific climate conditions, which might not be applicable to other regions.

The decision-making process for retrofitting buildings can be significantly impacted by the availability of retrofitting alternatives that are specially created for various climate zones (Liu et al., 2022). To increase the adoption of energy-efficient retrofitting solutions and reduce greenhouse gas emissions, it is advised to develop and promote options tailored to local climatic conditions, while considering the typology of the building. By adopting climate-specific retrofitting strategies, energy efficiency can be significantly improved by taking into consideration the unique weather conditions of a region.

3.2.2 Building retrofit assessment according to the surrounding environment

Besides climate factors, there are other environmental factors that are essential for reducing greenhouse gas emissions and improving energy efficiency in cities (Bouw et al., 2021). For instance, the architect must consider solar and daylight availability to optimize solar energy production and minimize environmental impact in design. By integrating sustainable and passive design solutions with active solar energy systems, cities can reduce their reliance on non-renewable energy sources and promote a more environmentally sustainable future (Webb et al., 2016). Many energy models have been developed recently, but they tend to neglect the importance of phenomena that occur at the urban scale, such as the effect of urban geometry on energy consumption (Mirzabeigi & Razkenari, 2022).

In conclusion, the surrounding environment and building design that considers solar and daylight availability are crucial factors in reducing greenhouse gas emissions and improving energy efficiency in buildings. While various energy models have been developed, they often neglect the impact of the surrounding environment on energy consumption. Therefore, it is important to consider factors such as building height, the density of the building in urban design, shape factors and etc, to optimize energy usage and minimize environmental impact. By integrating sustainable and passive design solutions with active solar energy systems, buildings can reduce their reliance on non-renewable energy sources and promote a more environmentally sustainable future. Overall, these findings emphasize the need for integrated approaches to urban planning and building design that prioritize environmental sustainability and energy efficiency.

4. DISCUSSION OF RESULTS

In order to determine the limitations and contributions of building retrofit assessments with regard to building typology and environmental factors, a review of the relevant literature was conducted in this research. This research aims to identify and evaluate the most relevant publications concerning building retrofitting assessments, with a specific focus on their respective key areas. The methodology involves the selection of 60 publications, followed by a thorough analysis of their contents. In this section, this paper selects 27 publications that align closely with its goals and methodology, and delves into their assessment methods (see Table 1). In addition, this paper thoroughly assesses the selected publications, examining their typological and geometrical parameters as evaluated in these studies. Furthermore, it considers other parameters such as the exploration of different climate conditions, cost analysis, CO_2 emissions, as performance metrics and various retrofitting alternatives. These factors are crucial to understanding the assessment of achieving low-energy retrofitting in residential buildings.

Table 1: Summarised Publications for Building Retrofit Assessment based on Focused Parameters

Evaluation criteria	Assessment method	Typology									Retrofitting											Energy performance					
		(Ballarini et al., 2017)	(Coma et al., 2019)	(Ballarini et al., 2011b)	(Dascalaki et al., 2011b)	(Beagon et al., 2020)	(Salehi et al., 2015)	(Kragh et al., 2014)	(Kristensen et al., 2021)	(Loga et al., 2016)	(Ignjatović et al., 2021)	(Bennadji et al., 2022)	(Alavirad et al., 2022)	(Wang et al., 2022)	(Alabid et al., 2022)	(Merlet et al., 2022)	(Carletti et al., 2014)	(Yazdi Bahri et al., 2021)	(Marasco et al., 2016)	(Lee et al., 2019)	(Liu et al., 2022)	(Kadrić et al., 2022)	(Sugár et al., 2020)	(Becchio, 2012)	(Q. Li et al., 2021)	(Aksamija, 2015)	(Xiong et al., 2019)
Architectural features	Geometry	X		X			X					X				X						X	X				
	Building size			X	X		X			X		X								X	X	X					
	Building age		X		X	X	X	X	X	X	X	X				X			X		X			X			
	Material	X		X	X	X		X					X	X			X		X	X		X			X	X	X
	Window to wall ratio					X										X	X					X			X		X
	Building layout												X			X											
	Building orientation																X										
	Building type					X		X			X		X								X		X	X			
	Various climate zones	X	X		X	X	X			X			X	X			X	X			X	X	X	X			X
Retrofitting and energy efficiency criteria	Thermal insulations	X	X		X	X		X					X	X	X		X	X		X		X			X		X
	Window replacement	X															X			X		X					
	Heating systems	X	X	X	X	X			X					X	X	X		X	X	X		X	X				X
	Humidity																	X									

	Cooling systems					x								x	x				x								x
	Water systems													x	x												
	Lighting performance													x	x		x	x	x			x				x	
	Shading devices																x									x	
	Acoustic performance																x										
	DHW		x	x															x				x				
	Ventelation												x	x					x								
	HVAC													x					x	x		x				x	
	Renewable sources											x		x	x				x	x						x	
	Retrofitting alternatives													x		x	x	x	x		x	x			x	x	
Performance metrics	Energy demand				x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x
	Energy cost		x										x	x	x	x			x	x		x					
	CO_2 emissions	x	x		x								x		x									x		x	
	Thermal comfort														x		x	x							x		x

The findings indicate that most of the publications propose retrofitting alternatives as solutions to improve energy efficiency and sustainability in buildings. However, there remains a lack of understanding regarding various metrics and calculation methods for evaluating retrofitting solutions, potentially hindering the development of standardized and readily available approaches. The studies identify that no single retrofitting solution can address all challenges, while also raising awareness about the importance of adoptable retrofitting strategies.

As observed in Table 1, the majority of the publications focus on implementing energy-saving techniques based on specific climate conditions and personalized retrofitting options. Nevertheless, it is crucial to recognize that certain limitations still require attention and resolution. Limitations in current liturature are outlined below:

- Several studies have been conducted, particularly in the last decade, to assess the energy efficiency of dwellings and improve building retrofitting according to their typologies. Although, most have used the "Typology Approach for Building Stock Energy Assessment" TABULA report to provide methods for classifying housing typology in Europe. However, there is still a lack of comprehensive information regarding technical developments, building structures, building layouts, and their relations which could affect energy requirements in buildings.
- TABULA report offers two levels of refurbishment for each typology, usual and advanced refurbishment. According to these refurbishment techniques, there is only one recommendation for each level but no elaboration on other refurbishment alternatives for each typology.
- The physical characteristics of buildings are regularly and significantly altered over time, changing not only the parameters of urban areas but also their physical characteristics and compositions. Therefore, there is a need to develop and amend adoptable retrofitting solutions based on building typologies.
- The energy-efficient building design methods have limitations when applied in regions with diverse climate characteristics. The method may not account for microclimatic conditions, extreme weather conditions or changes in building usage or occupancy patterns. It may not be suitable for regions with different building types or sizes and may require extensive data collection and processing.
- Numerous methods and tools have been created globally for assessing the energy efficiency of buildings. However, each of these methods and tools is different in its own way, and there is no consensus on how to score or weigh them. Furthermore, there is a shortage of building environmental assessment methods for retrofitting stages and approaches for determining carbon emissions and benchmarking are not consistent.

5. FUTURE STUDY DESIGN

In order to address the limitations observed in current liturature and develop more effective energy-efficient building retrofitting, a comprehensive approach is proposed for future studies.

- To address the lack of comprehension regarding the intricate connections among building layouts, technical progress, and energy demands, an in-depth building classification can be undertaken. This entails not only categorizing building typologies but also delving into the details of their structural compositions, architectural designs, and evolving technological aspects.
- Expanding on the predefined retrofitting solutions, a future study could focus on developing retrofitting alternatives tailored to various building typologies. This could involve an in-depth exploration of alternative refurbishment techniques precisely suited to specific building typologies. By considering an array of innovative materials, construction methods, and emerging technologies, researchers could propose retrofitting strategies that cater to the unique characteristics of each typology while also optimizing energy efficiency and sustainability. This approach would provide a richer set of retrofitting solutions for architects, designers, and stakeholders to choose from, ensuring a more adaptable and effective retrofitting process that aligns with diverse building needs and environmental contexts.
- To propose an adaptive retrofitting solution framework that aligns cohesively with diverse building typologies and could respond to their evolving physical features or environmental contexts. By incorporating advanced assessment methodologies, responsive strategies, and a unified assessment framework, the proposed adaptive retrofitting solutions aim to enhance the long-term performance and environmental compatibility of buildings.

6. CONCLUSION

Building retrofitting assessments have recently gained a lot of attention from researchers. Since 2019, the number of published works on this topic has increased significantly. The goal of this study is to thoroughly examine the available literature on the relationship between building typology and energy efficiency, with a particular emphasis on retrofitting. In addition, this study attempts to identify research gaps and plan a future study on the most effective energy-saving solutions for retrofitting various types of buildings while taking specific environmental and physical aspects into account. Based on the review of journal articles (n = 60) between 2011 and 2023, this study summarized: (1) building retrofitting, (2) energy efficiency improvement, and (3) building typology. The main findings of this study include the following: the current body of existing literature on building retrofits has primarily focused on classifying building typologies and tailoring retrofitting solutions accordingly. However, there is a significant gap in knowledge regarding technical advancements, building structures, environmental factors, and their relationship, as well as alternative strategies for executing standard or deep retrofitting and accurately predicting energy savings. The energy-efficient building design method based on climatic zoning has limitations when applied to diverse climates and building types/sizes, which necessitates the development of a comprehensive methodology and tool for transferring knowledge to support adoptable energy-efficient building retrofits. Addressing these deficiencies is crucial for developing responsive and adaptable solutions that are tailored to the unique characteristics of each building rather than relying on a generic approach. It would also facilitate designers and policymakers with relevant information on energy-efficient building retrofits to make informed decisions.

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A BIM-BASED APPROACH TO THE MANAGEMENT OF HISTORIC BRIDGES

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ABSTRACT: *Building Information Modelling applied to civil infrastructure has opened up interesting scenarios for integrated management of existing infrastructural works. In the last few years Bridge Management System (BMS) have been increasingly used by infrastructure owners, based on different control systems: from stochastic methods, which make it possible to define a condition ratio (CR) starting from periodic inspections of bridges, to sensors for structural monitoring, which can originate a flow of information exchange between real artifacts and the digital model capable of activating effective reactive or planned responses in the operation and maintenance phase of the asset.*

The paper intends to outline a BIM-oriented process workflow, which from the creation of parametric objects for infrastructural works using Scan-to-BIM acquisition techniques and procedures, arrives at the implementation of information bridge models to manage both static data from scheduled inspections of technicians of defects and their severity according to specific guidelines, and dynamic data from incoming and outgoing sensors placed in the physical asset for real time monitoring towards analysis, supervision and control systems of the facilities owner. The defined process workflow will be applied to some case studies, related to bridges of different characteristics, outlining some directions for future developments. In detail the research showcases the tasks undertaken and the outcomes achieved on four selected bridge case studies, which are real and situated within the geographical area of the Tuscany region, Italy. The studied bridges are all still in use and hold historical significance, as they were constructed between two hundred and one hundred years ago.

KEYWORDS: *Bridge Management System; InfraBIM; HBrIM; Digital Twin, Scan-to-BIM, SHM, IFC.*

1. INTRODUCTION

Generally, users perceive infrastructure projects as safe, and it's uncommon for drivers of regular vehicles to doubt the safety of the bridge they're crossing (Santarsiero et al., 2021). However, factors like extreme environmental conditions, mechanical loads surpassing the design assumptions, extended operational durations, inadequate maintenance, and similar elements can significantly impact and jeopardize the structural integrity of bridges (Saback de Freitas Bello et al., 2022; Santarsiero et al., 2021; Zinno et al., 2022).

After a series of incidents, including the Morandi Bridge collapse (Santarsiero et al., 2021), the Italian Government in 2020 enacted the "Guidelines on risk classification and management, safety assessment, and monitoring of existing bridges" through legislation (Ministerial Decree number 578/2020). The ministerial decree number 204/2022 essentially reaffirmed the aforementioned guidelines, extending their temporal validity to forty-eight months, or until the end of the year 2024. Further complementing the Italian regulatory framework are the "Operational Instructions for the Application of the Guidelines for Risk Classification and Management, Safety Assessment, and Monitoring of Existing Bridges" proposed by ANSFISA and annexed to the ministerial decree number 204/2022.

For the risks that older bridges run and for regulatory issues similar to those described above for the Italian case, in recent years, Bridge Management Systems (BMS) have gained much importance and numerous infrastructure management companies have adopted it. Particularly, those systems based on stochastic methods have gained prominence, allowing the determination of a Condition Ratio (CR) based on regular bridge inspections and on the detection of the defects of the bridges themselves. Bridge Management Systems (BMSs) are modular information systems with designated functions (de Freitas Bello et al., 2021; Woodward et al., 2001), including inventory compilation, preservation assessment, risk evaluation (including load capacity), operational management, cost estimation for maintenance strategies, deterioration prediction and associated costs, socio-economic importance analysis with budget constraints, maintenance priority setting, and multi-temporal budget tracking. BMSs, along with Structural Health Monitoring (SHM) techniques, are employed to assess bridges post-visual inspections by

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Carlo Biagini, Alberto Aglietti, Andrea Bongini, *A BIM-Based Approach to the Management of Historic Bridges*, pp. 1105-1116, DOI 10.36253/979-12-215-0289-3.110

specialized technicians.

The majority of current BMSs employ a two-dimensional (2D) approach to record and store information without visual representation and dynamic integration (Li et al., 2023). Building Information Modeling (BIM), which involves creating and managing a comprehensive 3D model embedded with informative data for the entire lifecycle management of a specific asset (Kaewunruen et al., 2022), emerges as the most natural source of information and data storage for next-generation BMSs.

In the field of the SHM it is now common practice to place sensors on the bridges that it is believed to have to check or monitor for what has emerged from inspections on the same. The type of sensors that can be installed varies according to the phenomenon to be monitored but also with respect to its purpose: it is possible to install different sensors for short, medium or long-term monitoring or to install sensors capable of sending an alarm when a certain threshold value is reached. Enhancing finite element method (FEM) analyses with continuous sensor data can bolster the reliability of studying degradation. Artificial Intelligence (AI), especially Machine Learning (ML), offers transformative potential for Structural Health Monitoring (SHM). ML techniques automate pattern recognition in sensor data, aiding defect detection and risk assessment (Malekloo et al., 2022; Zinno et al., 2022).

Considering AI as a predictive technology that utilizes data and "experience" to formulate forecasts, which in turn serve as inputs for the decision-making process, it can be asserted that the initial solutions conceived and applied to date across various fields, including Structural Health Monitoring (SHM), have been “Point Solution” where AI has replaced previous predictive tools (Agrawal et al., 2018, 2022). However, it is reasonable to anticipate a substantial paradigm shift in the medium term within this sector, as well as others. Stemming from the concept of reducing the cost associated with forecasting, a principal economic facet introduced by contemporary Machine Learning (ML) algorithms, a complete reorganization of SHM is foreseeable. Referring to this form of AI-based solution as a “System Solution” is appropriate.

The Italian Guidelines also envision the utilization of digital technologies for their "intelligent" administration, achieved by integrating sensors into SHM systems and constructing informative models of structures. This is regarded as a step towards the realization of the National Digital Archive of Public Works (AINOP).

A digital model integrating geometric and performance data aids SHM and aligns with the "Digital Twin" concept of Smart Manufacturing and infrastructure research. In the AECO sector, the Digital Twin concept is tied to Building Information Modelling (BIM). In the realm of bridges, the term "BIM" is often replaced with: InfraBIM (Osello, 2019), BrIM (Barazzetti et al., 2016; Saback et al., 2022), HBIM (Barazzetti et al., 2016; Borin & Cavazzini, 2019; León-Robles et al., 2019; Murphy et al., 2011; Stavroulaki et al., 2016), HBrIM (León-Robles et al., 2019).

In the field of built heritage, surveying plays a crucial role in comprehending structures. Contemporary techniques such as laser scanning(Boardman et al., 2018; León-Robles et al., 2019; Pritchard et al., 2017) and photogrammetry (Ioli et al., 2022; Jáuregui et al., 2006; Mohammadi et al., 2021) are widely employed, utilizing both ground-based tools and UAV systems. These methods generate datasets in the form of point clouds (PC), which then require further processing to create Building Information Models (BIM). Known as Scan-to-BIM, this process is well-documented in the literature(Croce et al., 2023; Roggeri et al., 2022; Sing et al., 2022; Wang et al., 2019).

The surveys and consequently the point clouds can serve at different stages in the useful life of a bridge:

- They can form the database foundation to create a BIM model if it doesn't already exist.
- They can be work an AS IS representation of the structure.
- In the capacity of AS IS, they can be used for comparisons with a BIM model representing a situation prior to the survey.

When a Building Information Model (BIM) of an existing bridge is being developed, several factors come into play that strongly affect the modeling process. These factors include the bridge's characteristics, how easy it is to access the bridge for data collection, and the availability of detailed design plans or information about the bridge's original construction and its current state. All of these elements have a significant impact on how the BIM model of the bridge is created and how accurate and comprehensive it can be. The process of creating a Building Information Model (BIM) from scanned data is easier for bridges with massive components like masonry structures. On the other hand, this process is more complex for bridges made of metal trusses. The complexity arises because metal truss bridges consist of many intricate elements with edges and corners that are difficult to accurately capture using laser scanning and photogrammetry techniques. It's easier to model massive bridges using scan-to-BIM methods compared to complex metal truss bridges due to the challenges of capturing detailed data.

With the widespread adoption of BIM as a methodology for building modeling, the IFC data schema, Industry Foundation Classes, has gained importance. Leveraging the principles inherent in Object-Oriented Programming (OOP), IFC presents a novel shared language across the entire Architecture, Engineering, Construction, and Operations (AECO) sector. IFC is not a replacement for the language of technician draw nor an evolution thereof; rather, it serves as a schema enabling the transmission of comprehensive information about a construction. This logically structured data extends far beyond mere geometric representation. As described above, IFC has become an essential component of knowledge incorporated into all leading university programs within the sector. With the upcoming version of IFC, the schema will expand into the domain of infrastructure, which until now has been only partially representable or represented using non-conventional methods.

The topics addressed by this research are relevant to Cluster 3 of the Horizon Europe 2021-2027 program and also dealt with in the 2021-2027 National Research Plan (PNR), in line with the objectives of Goals 9 and 11 of the 2030 Agenda of United Nations Organization.

2. MATERIALS AND METHODS

In recent years, the intersection of engineering, digital technology, and heritage preservation has paved the way for innovative approaches in the study of historic structures. This research article presents a comprehensive examination of the digital documentation and structural monitoring of four distinct historic bridges. By employing Building Information Modeling (BIM) techniques, each bridge was meticulously captured in a virtual environment, enabling a detailed analysis of its architectural and structural features. Furthermore, this study explores diverse strategies for the digital representation of these historic constructions and the implementation of structural monitoring solutions.

The preservation of historic bridges holds significant cultural, historical, and engineering value. Through the integration of BIM methodologies, these bridges can be accurately documented and analyzed, facilitating the development of effective strategies for their maintenance and conservation. The four selected case studies serve as tangible examples of this interdisciplinary approach, shedding light on the challenges and opportunities that arise when dealing with the intricate balance between preserving heritage and ensuring structural integrity. By examining the challenges and successes encountered in the digital documentation and structural monitoring of historic bridges, this study aims to inform best practices and inspire further advancements in the field.

Fig. 1, 2: Masonry bridge over Masera Ditch | Laser scanner survey.

2.1 Case Study 1: Masonry Bridge over the Masera Ditch

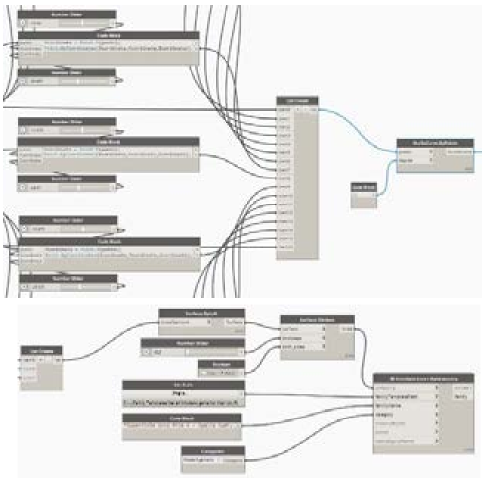
The masonry bridge over the Masera Ditch is situated in the Crespino over Lamone-Biforco section of the railway line connecting Borgo San Lorenzo to Faenza. The “Faentina” Railway is a state-owned railway line that connects Florence to Faenza via Borgo San Lorenzo (fig. 1). Its construction took place between 1880 and 1893, with the idea originating as far back as the 1840s. This railway was closed for an extended period due to significant damage sustained during World War II. Traffic resumed partially in the 1950s, but the line experienced another closure in 1971. The gradual reopening began in the 1990s and was completed in the early 2000s. Essentially, it’s a sparsely utilized line, hence its lack of electrification and the presence of a single track.

The bridge over the Masera Ditch is a masonry structure with five arches, situated on a curved path. At its highest point, the structure stands 40 meters above the ground. Adjacent to the bridge, both upstream and downstream, are two galleries manually excavated from the rock.

2.1.1 Documentary research and survey campaign

No original bridge designs have been found, nor have any other technical drawings of any kind been located. Near the bridge, there is an access point to regular road traffic, and it's also possible to ascend the mountain to reach little clearings at the bridge's height, away from the rail track. Given the scenario described in the preceding paragraph, a significant portion of the survey was conducted without the presence of surveillance personnel. However, this did involve a temporary suspension of railway traffic.

The survey campaign was conducted using a Z+F IMAGER 5016 Laser Scanner, which also captured RGB data (fig. 2). Additionally, photographic documentation was captured using a Sony H300 Camera with 35x optical zoom. The point cloud datasets were captured in .fls format and subsequently imported into Autodesk Recap® software.



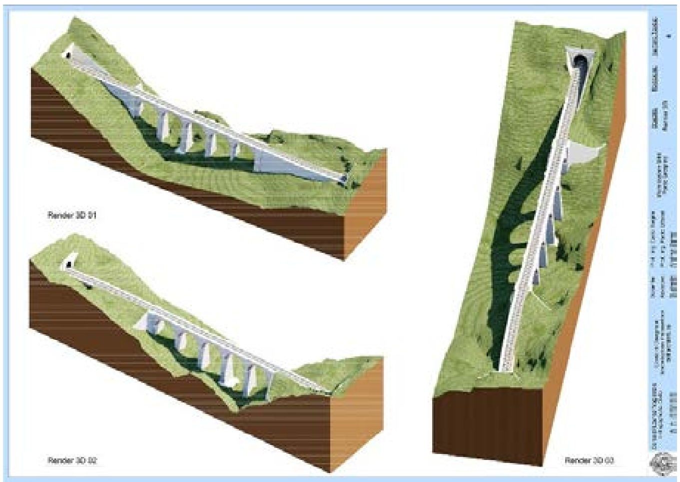


Fig. 3, 4: VPL script for arches modelling | Views of the BrIM model

2.1.2 BIM Modeling and Implementations

Given the absence of technical drawings for the bridge, in the case study of the Masonry Bridge over the Masera Ditch, a BIM modeling was carried out using a conventional Scan-to-BIM workflow.

The initial step taken towards modeling the viaduct involved refining the provided point cloud data. This was achieved by removing portions of the surrounding vegetation and segmenting the point cloud into three parts, aimed at reducing the file size to expedite the modeling process. Subsequently, these three segments of the point cloud were integrated into Revit to initiate the modeling process. The bridge has been decomposed into its constituent elements based on the methodologies employed by the management company of the Italian railway line, similarly to what was done for the case study of the metal girder on the Osa river. The three segments of the point cloud were successively integrated into the Revit environment, and reference grids were generated from them. These grids were then utilized to position individual components in subsequent stages.

Chronologically, the first elements that were modeled are the viaduct piers. For the BIM component describing the piers, the parameters that have been made parametric include the height, dimensions of the upper rectangular base, and the various inclinations characterizing the short and long sides of the pyramid. Based on these dimensions, the dimensions of the lower rectangular base were then defined. Furthermore, the material with which the piers were constructed has been made parametric and based on observations of images and the point cloud, masonry was chosen as the material. The arch surface was generated using the Dynamo platform, as the represented form exhibits a complex double curvature that is challenging to model otherwise (fig. 3). Initially, commands were implemented in Revit to select the edges on which the arch relies. Subsequently, median points of the segments were placed to create a central line. Alongside two other lines positioned at the ends of the selected segments, these components facilitated the creation of the arch surface.

The subsequent step involved establishing control points on the previously generated lines. Each control point was defined with its respective height relative to the arch springing level and the setback. Following this, a curve was constructed. Finally, after executing these procedures for the three segments that define the curve, the surface was generated and assigned a thickness. Ultimately, the thus-formed geometry was incorporated into the Revit project. The abutment and backfill were modeled using the "Generic Models" category. Both components were initially modeled as solid forms, and subsequently, the shape of the arch was subtracted using an empty arch model. For these elements, in addition to the parameters defining their shapes, a material attribution parameter was introduced. For the abutment, the material is masonry, while for the backfill, it is railway crushed stone (fig. 4).

2.2 Case Study 2: Giorgini Bridge over the Bruna River

The presented case study revolves around the "Giorgini Bridge" in Castiglione della Pescaia (Grosseto, Tuscany Italy), build from 1827 to 1828 as part of the Maremma reclamation works (fig. 5). Designed by mathematician and civil engineer Gaetano Giorgini, the bridge was constructed across the Bruna River. The bridge featured three floodgates, aimed at preventing the intermingling of Bruna River's freshwater with the saline seawater. The construction, initiated in 1827, aimed to address the belief that this mingling caused malaria, belief of the time which later proved to be scientifically unfounded. The bridge, 26 meters wide and 12 meters high, is composed of lateral shoulders, lowered round arches, and pylons. Positioned between these pylons were three floodgates enclosed in oak and framed with metal. These floodgates rotated on iron pins, closing manually or automatically via high-tide currents, preventing seawater intrusion into the marsh. During low tide, the force of the lake water facilitated the opening of the floodgates, discharging water into the sea.

Fig. 5, 6, 7: View of Giorgini Bridge | Digital photogrammetry from drone | Views of the BrIM model

2.2.1 Documentary research and survey campaign

The investigation involved multiple methodologies: a laser scanner was utilized for acquiring geometric data, and a drone facilitated a photogrammetric survey. This was further supplemented by a topography network (polygon) for survey phases. The approach encompassed a sequence of steps, starting with a total station and GPS survey, followed by drone-based photosets creation, and concluding with the generation of a point cloud through a laser scanner.

The instruments employed in the survey campaign are: a SOKKIA SET3 130-R3 total station, a TOPCON GR-3 GPS receiver, optical prisms, a DJI 3 Phantom UAV, and a FARO FOCUS CAM2 laser scanner. The drone flight was organized using the Altizure® application, enabling the definition of the GPS-coordinated flight path. Subsequently, the photographic dataset was post-processed with Agisoft PhotoScan® software to generate a point cloud. Meanwhile, the laser scanning dataset underwent processing using Autodesk Recap® software (fig. 6).

The comparison in terms of "deviation of the cloud of points", to evaluate the difference between the two clouds generated using different data acquisition technologies, was performed with Cloud Compare open-source software. The original design drawings were retrieved, and their accuracy was subsequently verified during the BIM modeling process. This validation was achieved by comparing them with the point clouds obtained from the previously described survey campaign.

2.2.2 BIM Modeling and Implementations

To develop the H-BIM model representing this unique historical infrastructure, a semantic deconstruction was required. This involved defining individual BIM components ranging from primary structural elements to intricate detailing components (fig. 7).

Both point clouds were imported into the chosen BIM modeling software, Autodesk Revit®. By concurrently utilizing the point clouds and the original design drawings, each component of the structure was meticulously modeled one by one. The metal components of the bridge were primarily modeled using the original design plans, whereas the masonry components were predominantly elaborated based on the point clouds.

2.3 Case Study 3: Metal Truss Bridge over the Osa River

The subsequent case study pertains to a dual-track metal truss railroad bridge that dates back to the early 1900s. This bridge remains operational, spanning the Osa River in Italy as part of the Albinia-Talamone railway section on the Rome-Grosseto line, which is managed by RFI (Rete Ferroviaria Italiana), an Italian railway company (fig. 8). The metal bridge boasts a 42-meter span and features abutments constructed using a composite material of masonry and concrete. Notably, a diverse array of components deviating from standard commercial metal profiles can be observed. These elements consist of a combination of "plate" profiles, each implemented with distinct configurations, and they incorporate supplementary reinforcement plates in the areas subjected to the highest stress levels. The connections between disparate components were forged using plates and secured with hot-riveted nails.

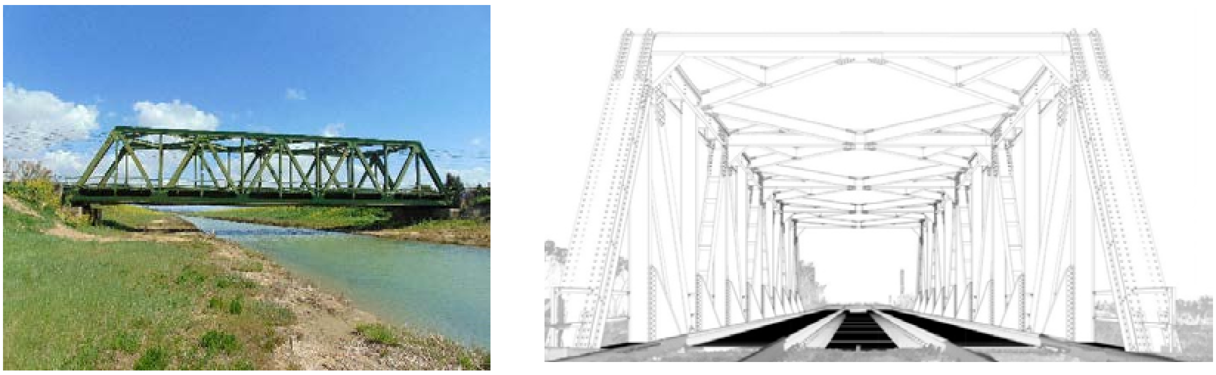


Fig. 8, 9: View of metal bridge over OSA River | Perspective view of the BriIM model

2.3.1 Documentary research and survey campaign

The original design documentation for the metal bridge has been retrieved, comprising seven technical drawings. Additionally, there are documents pertaining to the materials used in the bridge, the conducted load tests, and other activities related to the construction phases. The survey campaign was executed utilizing the Faro® Focus 3D x 330 Laser Scanner. The survey operations were meticulously scheduled to coincide with intervals when train traffic was absent. At the time of the survey, the riverbed exhibited cleanliness and optimal condition. The point cloud datasets were captured in .fls format and subsequently imported into Autodesk Recap® software. This software facilitated the alignment procedures for the distinct scans acquired during the campaign.

2.3.2 BIM Modeling and Implementations

The bridge has been conceptually broken down into constituent elements following the procedures utilized by the management company of the Italian railway line. Given the presence of detailed original designs, the BIM modeling of the various bridge components was based on these drawings. The point cloud obtained as a result of the survey campaign was used as an "AS IS" comparison for the modeled components. The comparison was possible with the Cloud Compare open-source software (fig. 9).

The chosen modeling workflow was partly influenced by the availability of the original technical drawings and partly dictated by the complexity of the metal truss. This truss comprises a high number of components that include edges, vertices, perforated elements, and other geometric intricacies, making its survey using a Laser Scanner challenging and difficult, along with the subsequent generation of a point cloud representation. The software used for BIM modeling was Autodesk Revit®. Given the uniqueness of the bridge components, a family was created for each type of element, and a report was produced for each of them.

The concept underlying the breakdown into "elements" logic, as provided by the Italian railway company, aligns with the D.O.M.U.S. Software. This software aids maintenance engineers in the railway infrastructure sector in evaluating the condition and preservation status of bridges. A dedicated master dataset is employed for cataloging both the structures and their identifiable defects. These defects are linked to corresponding indices, facilitating the algorithm in forming assessments.

During the inspection visit, engineers identify and photograph each defect present on the bridge, utilizing official catalogs and documenting the specific bridge component affected by each defect. Based on the previously mentioned data encompassing the geometric configuration of the bridges and inspection outcomes, the algorithm computes some indices. These indices are associated with a particular level of defectiveness, aligning with the established protocol for inspecting railway structures. Through assigning level of defectiveness, the bridges, infrastructure management gains the ability to ascertain priority interventions and make well-informed choices concerning measures for mitigating risks.

The operationalization of the management software functionalities was achieved through a synthesis of Python code scripts utilized within the visual programming environment (VPL) Dynamo. These scripts were integrated with Excel spreadsheets and an Access database, encompassing various tables and numerous queries, the latter of which were scripted directly in SQL language. The Dynamo-developed algorithm is composed by several interconnected node clusters in groups, each of them serving distinct functions. These functions include querying the BIM model for crucial input, exporting datasets to Excel, enabling automated interactions between Excel and Access, reading and importing externally processed data, and ultimately recording achieved results – or macro-outputs – within pertinent fields in BIM environment (fig. 10).

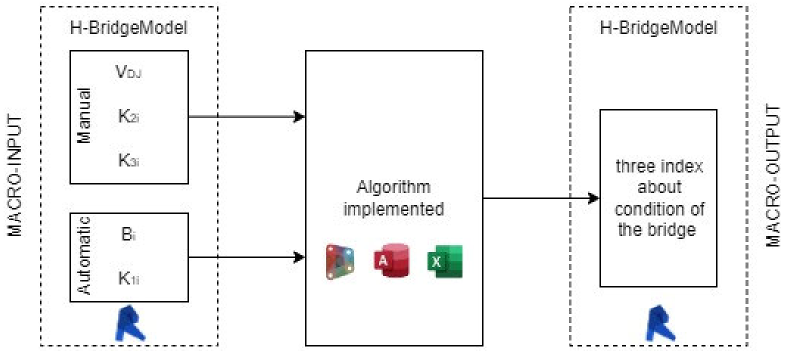


Fig. 10: Data flow. From macro-inputs to macro-outputs

The implemented management functionalities within the BIM environment enable railway engineers to record bridge defects directly in the BIM environment, execute the Dynamo algorithm, and access the calculated indices in the same software. Finally, an IFC model of the metal truss over the Osa River was generated in accordance with the IFC4 standard. In this model, bridge components were categorized as follows:

- all beam-like components have been converted into IfcBeam instances;
- flat metal profiles have been translated into IfcPlate instances;
- bolts have been categorized as IfcMechanicalFastener instances;

- masonry abutments are classified as IfcBuildingElementProxy instances;
- supports have been transformed into IfcBuildingElementProxy iinstances.

With the upcoming release of IFC 5 and its corresponding implementation by commercial software, it will be possible to more accurately map the elements of an infrastructure.

2.4 Case Study 4: Toppoli Bridge over the Arno River

The presented case study pertains to the Toppoli Bridge located over the Arno River near Bibbiena in the Province of Arezzo (Tuscany, Italy) (fig. 11, 12). This bridge, originating from the early 1900s, was constructed using traditional building techniques. The structure comprises a substantial masonry construction featuring a dual arched span. Each arch possesses dimensions of 19.60 meters in length, 3.00 meters in height, and 5.00 meters in width. The piers and abutments are constructed using square stone masonry, while the arches are composed of brick masonry. In the approximate timeframe of the 1960s, a noteworthy event involves the expansion of the road deck. This expansion entails a reinforced concrete slab measuring around 7.50 meters in width and 0.25 meters in thickness. This slab extends out as a cantilever from beneath the masonry arches.

Fig. 11, 12: Views of Toppoli Bridge over the Arno River

The bridge was part of a 2019 experiment in multilevel methodology, conducted through a collaboration between the Tuscany Region Administration and the Regional Federation of the Orders of Engineers of Tuscany. This initiative aimed to analyze and inspect priority bridges efficiently. The experience prompted the authors to develop an innovative BIM-centered approach for bridge risk management and monitoring.

2.4.1 Documentary research and survey campaign

No archival records of Toppoli Bridge original design have been discovered. The acquisition of geospatial data was achieved through a laser scanner survey, facilitating the creation of point clouds compatible with the chosen BIM authoring software, Autodesk Revit®. Prior to importing, the point clouds underwent necessary adjustments within Autodesk ReCap® software. This included aligning the scans into a unified model and reducing the point count to eliminate redundancies and the noise. The point cloud was then stored in .rcp format for seamless integration into Autodesk Revit® software.

2.4.2 BIM Modeling and Implementations

The preliminary BIM model was established utilizing system families, followed by the development of customized loadable families to represent specific components. Throughout this process, the aim was to adhere to the classification structure outlined in the CNR classification of masonry bridges. To model individual components, the point cloud was segmented, component by component, using the open-source software Cloud Compare. Each point cloud segment was then employed for BIM-based modeling of the corresponding component, either directly or by extracting sections in .dxf format (fig. 13).

Utilizing the DB-Link plug-in, model information from the Toppoli Bridge BIModel was exported and integrated into Microsoft Access software. This facilitated real-time updates reflecting any alterations made to the model. Any changes made in either Revit or Access were synchronized seamlessly between the two. Moreover, modifications to the database could be propagated back to the BIM model in Revit.

A BIM-centric system was established to manage sensor data, with a focus on accelerometers. In the case study, a WIT-type accelerometer sensor capable of capturing angle, acceleration, angular velocity, and magnetic field along the 3 XYZ axes was employed. The acceleration measurements exhibit an error rate of approximately 1%, with a capacity to record accelerations up to 16g. Extracted data can be exported in .txt format and imported into spreadsheets for generating graphs that depict accelerations along the three axes (fig. 14).

Building on the earlier described implementation process, the default information model in Autodesk Forge® software was substituted with the Toppoli Bridge HBrIM model, functioning locally. This model integration includes all essential tools for querying and editing the model. Additionally, it offers a comprehensive view of both the overall model and individual elements. Reference "sprites" are created within the model, i.e. icons that simulate the position of the sensor in the artefact. The setting then of a "sprite" within the model allowed the visualization of data obtained from the sensor directly on the screen. Notably, the study's scope primarily concentrated on optimizing the workflow process and did not delve into the technical and operational management of sensors installed on the bridge.

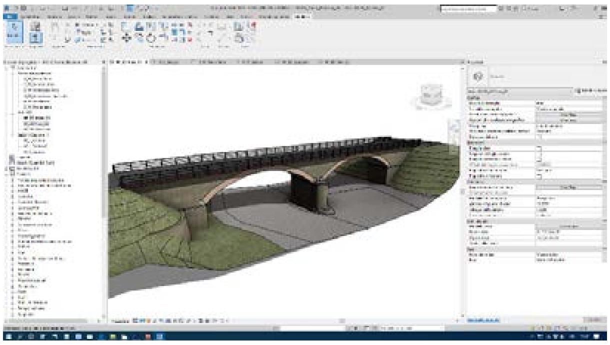
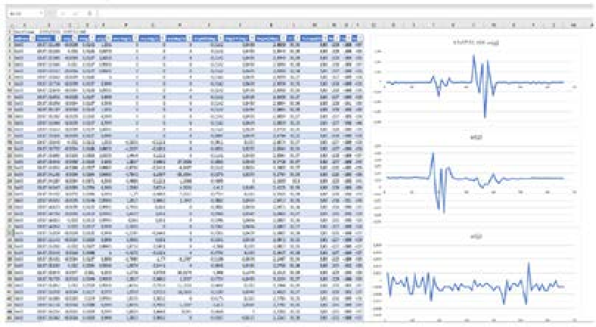



Fig. 13, 14: View of BrIM model | Representation of data by sensor device in a data sheet.

3. RESULTS AND DISCUSSION

3.1 Results

The results of the topographic survey campaigns and experiments conducted for each distinct case study are presented below.

1) Masonry Bridge over the Masera Ditch - The laser scanner survey campaign yielded excellent results, partly owing to the bridge's composition of easily distinguishable massive elements. RGB data was acquired. The workflow in this case was forced given the absence of technical documents. Using the Dynamo platform, a dedicated tool was developed to model elements characterized by double curvature, in this specific case the arches of the bridge. The tool described above produced the desired results and can be reused in similar situations, which are often encountered in the study of the heritage of Italian historic bridges.

2) Giorgini Bridge over Bruna River - The point cloud generated by the laser scanner comprise a total of 19 million points, while the one generated by UAV photogrammetry reached the size of 14 million points. The comparison in terms of standard deviation between the two point clouds, conducted using Cloud Compare, yielded optimal results.

3) Metal Truss Bridge over the Osa River - The survey campaign on the metal truss proved to be challenging due to its complexity. Given its numerous components and the sharp angles that define them, acquiring the bridge's geometry using laser scanners is hindered by the inevitable presence of "shadowed areas" in the acquired dataset. The chosen modeling workflow was partly influenced by the availability of the original technical drawings and partly dictated by the complexity of the metal truss described above.
The implemented management functionalities within the BIM environment enable railway engineers to record bridge defects directly in the BIM environment, execute the Dynamo algorithm, and access the calculated indices in the same software. In the generated IFC model, bridge components were categorized as follows:
- all beam-like components have been converted into IfcBeam instances;
- flat metal profiles have been translated into IfcPlate instances;
- bolts have been categorized as IfcMechanicalFastener instances;
- masonry abutments are classified as IfcBuildingElementProxy instances;
- supports have been transformed into IfcBuildingElementProxy instances.

With the upcoming release of IFC 5 and its corresponding implementation by commercial software, it will be possible to more accurately map the elements of an infrastructure.

4) Toppoli Bridge over the Arno River - The laser scanner survey campaign produced outstanding results, in part due to the bridge's makeup of clearly distinguishable large components, similar to what was previously noted for case study 1). A two-way connection between the BIM model in Revit, viewed as a collection of elements, and a dedicated database created in Microsoft Access has been developed and tested, yielding satisfactory results. A workflow was tested and optimized to connect a sensor, specifically an accelerometer, with the BIM model of the Toppoli Bridge. The objective was to visualize the sensor's output on the Autodesk Forge platform. Historical sensor data was used in the test; nevertheless, it is possible to achieve the same result with real-time data using a more powerful software version and a connected sensor.

3.2 Discussion

The present study aimed to offer a contribution to the development of Structural Health Monitoring systems in the context of transport infrastructures and bridges in particular, in line with the recent orientations of the technical-scientific community, both at the national and European level, on risk management and assessment.

The application of Building Information Modelling tools and methodologies was the first step in the information management of bridge knowledge. The obtained BIM models for the various studied bridges demonstrate the reliability of the scan-to-BIM methodology for modeling both infrastructure and bridges, just as it is for buildings. The conducted survey campaigns vary in terms of the instruments used and the surrounding conditions. Consequently, these experiences are valuable for identifying common factors that have influenced them: the intrinsic nature of the bridge and the materials of which it is made, the ability to suspend bridge usage, the size of the river or obstacle crossed by the bridges, the overall accessibility of the structure, and the economic and time costs associated with potentially repeating the survey campaign.

The most significant factor influencing the choice of BIM modeling workflow is the presence or absence of reliable design documentation. In the case of historical bridges, a survey campaign is essential. However, for some cases, the survey results become the primary or sole dataset for modeling, while in others, they serve only as a comparison. The processes of implementing bridge information models from the geospatial data acquisition phases conducted with laser scanning or 3D image surveying techniques show an adequate level of maturity for the intended and foreseeable uses in bridge control and monitoring activities. In particular, the use of scripts created in Visual Programming Language (such as Dynamo) into the BIM authoring software allows for the effective handling of complex shapes, which are derived from the geometric-constructive rules used in the design of railroad tracks and artwork in the late 1800s.

At the interoperability level, it has been demonstrated that translating a BIM model of a bridge into the IFC schema is already feasible, although currently, there are occasional challenges in classifying certain elements. Geometric data, however, is readily translatable into the IFC data schema. On the contrary methods of managing data from bridge monitoring can vary widely depending on the criteria set by the owner, which based on its strategic goals and internal organizational structure may define different approaches in terms of Asset Management System and related supporting technological infrastructure.

An initial strategy for enabling a "smart" approach to bridge risk assessment has been developed in the fourth study case, involving the implementation of a continuous data acquisition process through sensors installed on the physical structure. This approach leveraged the cloud-based Autodesk Forge platform, seamlessly integrated with BIM authoring software for information models. The functionalities of the corporate software assisting engineers in evaluating the safety and maintenance condition of railway bridges have been replicated within the BIM environment in the third case study. It was possible to provide information necessary to support decision-making regarding prevention and mitigation of natural and anthropogenic hazards, that pose a threat to the stability of the examined bridge and the integrity of the infrastructure network.

4. CONCLUSION

The conducted studies demonstrate the benefits achievable through the approach 'BIM - first of all', which prioritizes the use of BIM models at the core of bridge management processes for these infrastructures.

The approach used in the proposed experiments, can be attributed to the economic concept of a "Point Solution", whereas the more desirable approach for Bridge Management Systems (BMS) is certainly a "System Solution". This implies a comprehensive rethinking of BMS within the context of BIM and AI integration, aiming for a comprehensive and holistic solution.

The topics covered occupy a prominent place in the National Research Plan 2021-2027, particularly in the areas related to security and digital innovation. This is in line with Cluster 3 of Horizon Europe 2021-2027 and supports goals 9 and 11 of the United Nations Agenda 2030, which focus on resilient infrastructure, innovation and sustainable urban development.

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AS-BUILT DETECTION OF STRUCTURES BY THE SEGMENTATION OF THREE-DIMENSIONAL MODELS AND POINT CLOUD DATA

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ABSTRACT: *At construction sites, as-built management is generally conducted by taking pictures or surveying with total stations and comparing the images or survey data with design drawings or Building Information Modeling (BIM) models. Since this work is time-consuming and error-prone, more efficient and accurate methods using advanced Information and Communication Technology (ICT) are desired. Therefore, this research proposes a method that can efficiently capture the progress of construction by detecting each constructed structural member, such as beams, columns, connections, etc. In this proposed method, construction engineers first take many pictures of the construction site and conduct automatic image segmentation using a pre-trained Convolutional Neural Network (CNN) model. Next, point cloud data is generated from taken pictures by using Structure from Motion (SfM). Then, the point cloud data is semantically segmented by overlapping the segmented images and point cloud data using the pin-hole camera technique. Finally, the design BIM model and segmented point cloud data are overlapped, and constructed parts of the BIM model can be detected, which can be reported as as-built parts. A prototype system was developed and applied to an actual railway construction project in Osaka, Japan for testing the accuracy and performance of the system.*

KEYWORDS: *Construction progress management, Instance segmentation, Point cloud, Building Information Modeling.*

1. INTRODUCTION

Construction site management involves inspecting the completed parts of a construction project to ensure that the work is within specifications and contractual requirements. This task requires construction workers to compare the actual construction with the provided drawings and documents. The goal is to ensure that the construction is performed correctly and to calculate the corresponding contract price. Traditionally, construction management relied on drawings, but the use of 3D models has become more prevalent. These models enable better visualization and consensus building among stakeholders. While image data and laser scanners have been used in previous studies to create 3D models, large-scale structures and deep learning techniques have not been fully utilized for construction site monitoring. The succession of technical skills in the construction industry has been identified as an issue, prompting the need for changes in the construction production system. Leveraging technology advancements, such as 3D models and sensor information, has improved efficiency and contributed to various aspects of construction, including design, management, and maintenance. Building Information Modeling (BIM) is a lifecycle management system that facilitates efficient building maintenance. However, the process of collating 3D models with 2D drawings is time-consuming and prone to human error. Structure from motion (SfM) is a method used to acquire 3D data of existing structures, but converting point cloud models to polygon models presents challenges such as removing unnecessary details and setting appropriate thresholds. Efforts are needed to develop more efficient methods for capturing the current 3D model of a structure.

Recent advancements in deep learning and object detection technology have automated tasks such as construction site inspections, including identifying deformations and damages from images. The availability of large image datasets, such as ImageNet, has greatly improved object recognition accuracy using deep learning algorithms. In addition, recently, much research has been done for classifying point cloud data using deep learning (Charles et al. 2017). However, much research is required to classify civil infrastructure members.

Thus, this research has adopted a more simple 2D object detection method using deep learning and a pin-hole camera method and combined it with 3D BIM models to reproduce the construction situation on a 3D model and calculate construction costs. A training dataset specific to construction members was created to fine-tune existing deep-learning models. The proposed method enables efficient shape detection and attribute identification of construction elements and should contribute to the integration of detection information into 3D models, facilitating the creation of as-built models.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Nobuyoshi Yabuki, Tomohiro Fukuda, Ryu Izutsu, *As-Built Detection of Structures by the Segmentation of Three-Dimensional Models and Point Cloud Data*, pp. 1117-1124, DOI 10.36253/979-12-215-0289-3.111

2. RELATED WORKS

Before the advent of deep learning-based object detection, selecting features for object detection was challenging, especially in complex construction sites with various members and intricate structures. Past research in the field of construction has focused on automating tasks such as progress and productivity management using deep learning. One study proposed a system to automatically recognize completed parts in construction site images, but the detection results were not applicable to other systems, and accuracy was limited for complex-shaped structural members (Fathi et al., 2015). Research combining automation technology and BIM has aimed for efficient work (Kropp et al., 2018; Park et al., 2018), but perfect automation remains elusive due to the need for human intervention.

Another study developed a management system using a 3D model and proposed a method for constructing original models by detecting structural members in existing bridges from point cloud data (Lu et al., 2019). However, the method faced challenges in detecting complex geometric structures such as concrete or truss bridges. A laser scanner is used to create detailed BIM models of existing facilities but encountered difficulties with complex structures and occlusion (Tang et al., 2010). Various approaches have been attempted to create 3D models of existing buildings (Bosche et al., 2009; Brilakis et al., 2010).

Recent advancements in computer vision technology have enabled the automation of tasks performed by the human visual system. One study developed a system that automatically detects construction members in a room using 2D image data (Hamledari et al., 2017). Other studies have attempted to capture construction status and shape from image data (Gidaris et al., 2015; Khaloo et al., 2015). Perez-Perez et al. (2021) developed a method for the segmentation of indoor point clouds via joint semantic and geometric features for 3D modeling of the built environment. Pan et al. (2022) proposed geometric digital twins of buildings with small objects by fusing laser scanning and AI-based image recognition. However, the detection of different material members and multiple structure types for outdoor civil infrastructures remains challenging. Therefore, this research aims to fill this gap to improve the performance of as-built detection of civil infrastructures under construction for better construction site management.

3. PROPOSED METHOD

The proposed method aims to recreate the construction status in an as-built 3D model by incorporating the shape information from the detection result images obtained through a deep learning model. This allows for cost calculations without the need to match 2D drawings with the construction progress. The positional relationship between the detection result images, the completed 3D model, and a point cloud model generated using Structure from Motion (SfM) are matched.

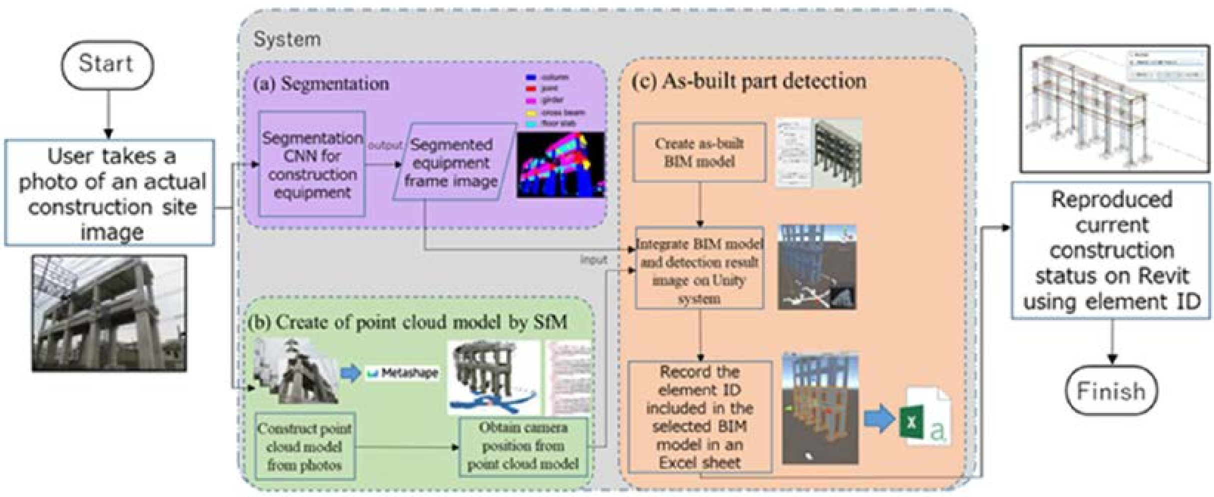

Fig. 1: Method overview.

As shown in Fig. 1, the method consists of three main steps: (1) performing segmentation detection using a fine-tuned deep learning model to identify structural members in the construction images, (2) creating a point cloud model using Agisoft Metashape to determine the 3D positions of the images, and (3) integrating the completed 3D model, detection result images, and point cloud model in a volume detection system using the Unity game engine. The positional relationship is established, and the identified structural members are recorded in an Excel sheet. Finally, the construction status is reproduced in BIM software (Revit), and the attribute information of the structural members is used to calculate the construction cost at the time of shooting.

3.1 SEGMENTATION

In this study, the weights of a U-Net model trained on the Cityscapes Dataset (Cityscapes Dataset, n.d.) were adjusted to distinguish structural members and the background. By updating the weights of the 37 layers, the positions and attributes of the structural members in the captured images could be identified. These detection results were treated as the finished form, providing insights into the construction site's situation. Since there were no published trained models for construction members such as columns, beams, and ducts, a training dataset was created using interior photographs of buildings under construction. The dataset was manually annotated using Adobe Photoshop CS4, creating mask images for each target member. The existing trained model was then fine-tuned using the mask images and the corresponding color changes in the original images.

In this study, a U-Net model trained on the Cityscapes Dataset was fine-tuned and used as a CNN for object detection to detect construction structural members from images, specifically targeting the five main structural members (Fig. 2).

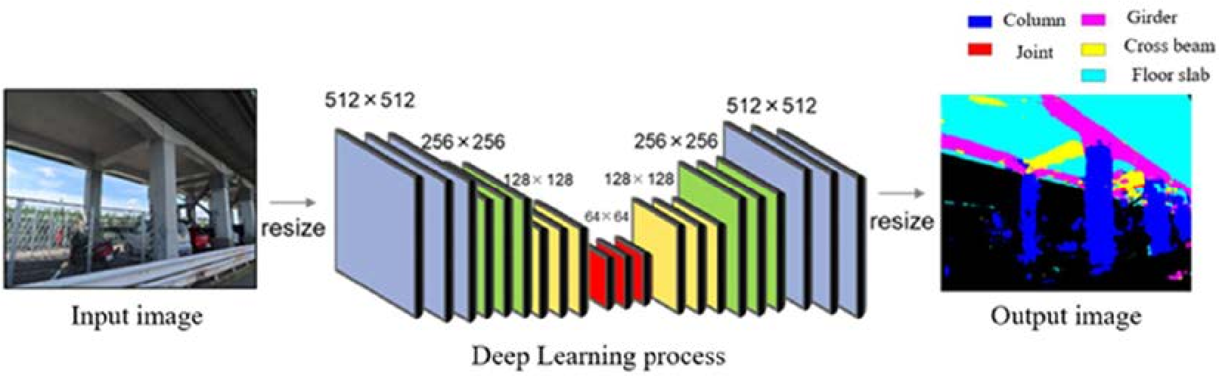

Fig. 2: U-Net-based CNN structure and learning results (example).

Meanwhile, a three-dimensional model representing the real space, including the camera position and target structure, was created using Structure from Motion (SfM) and Agisoft Metashape, a software for photogrammetric processing and 3D spatial data generation. Fig. 3 shows the results of fine-tuning U-Net using the created training dataset, where IoU stands for Intersection over Union.

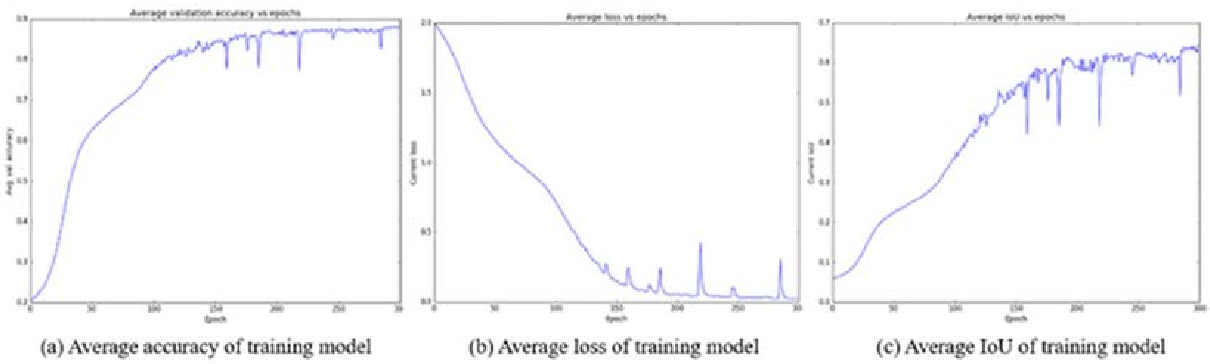

Fig. 3: The results of fine-tuning U-Net using the created training dataset.

The deep learning model in this study does not exhibit over-learning. The average accuracy for the training dataset increases, but the average loss for the test training dataset does not decrease. The detection accuracy of the fine-tuned model is evaluated using the average IoU value, which is 0.6428 at the 300th epoch. The IoU value measures the overlap between the correct answer area and the predicted area, indicating the model's performance. The evaluation index IoU indicates the numerical value obtained by dividing the overlapping part of the correct answer area and the prediction area by the union part of both areas, as explained in equation (1).

$$IoU \text{ (Intersection over Union)} = \text{(Intersection of detection areas)}/\text{(Union of detection areas)} \quad (1)$$

3.2 POINT CLOUD MODEL CONSTRUCTION

It is difficult to reproduce the positional relationship of the construction status when each image and model is imported into the game engine Unity in the lack of coordinate information. Therefore, we use SfM and Agisoft Metashape software to create a three-dimensional model that replicates the camera position and target structure in virtual space. Metashape allows us to process digital images and generate 3D spatial data, enabling the scanning of both small objects and large buildings. By analyzing the overlapping shooting locations in the photographs, we can calculate the distance to the subject in each photo.

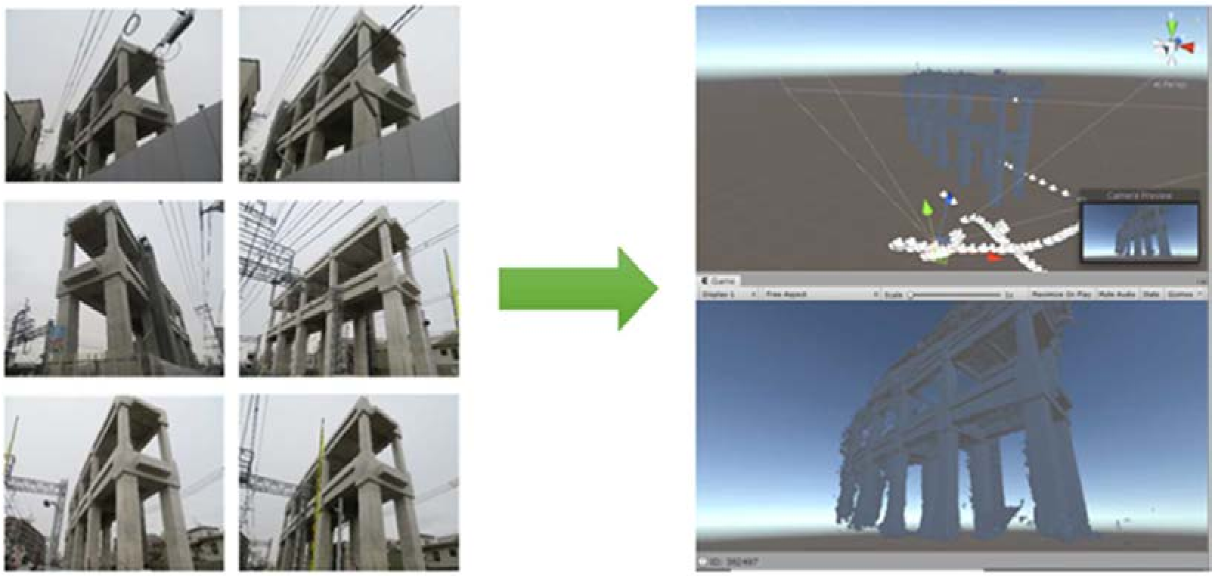

Fig. 4: Transfer from real frame to SfM model.

The gray model consists of a mesh overlaying a point cloud model created in Metashape, while the white object represents a virtual camera. As shown in Fig. 4, we can confirm the accurate reproduction of the camera's position and the target structure in Unity. Valid values for camera parameters such as position and rotation were confirmed in Unity, indicating successful reproduction of the real-world positions of the target structure and the camera in the game space. By overlaying the SfM model with the expected BIM model, a work detection system was created. The deep learning model performs object detection using the created mask image, adjusting the position and rotation coordinates of the virtual camera based on the mask image's parameters. The field of view on the virtual camera side is also adjusted to match the mask image. These preparations enable the replication of the construction situation in the game engine and the reflection of the deep learning model's detection results onto the BIM model.

4. EVALUATION

A case study was conducted on a building under construction at Osaka University to verify the proposed method. The system was tested by creating a BIM model from construction drawings and capturing photographs at the construction site, allowing for the verification of volume detection using a point cloud model. The system was implemented and tested using Unity on a standard PC with an Intel Core i7-3770K CPU and 32 GB RAM.

The detection result image from the deep learning model is utilized as a filter to extract and choose the completed portion from the generated BIM model. By aligning the aspect ratio of the Unity camera with the actual image size, the system excludes the undetected background area that is still under construction, ensuring only completed members are selected such as shown in Fig. 5.

In order to apply the image filter to the application, multiple angled frames are captured and went through a deep learning model with different weights. Fig. 6 shows part of the detection results

Fig. 7 shows the generated model in Unity and Revit. The detection results on the left if it indicates the accurate detection of completed ducts. However, upon examining the member model based on element ID, it was found that four beams on the front side of the third-floor slab were missing. Additionally, low detection accuracy is observed for elements not included in the learning dataset, such as overhead poles, scaffolds, and multiple electric wires, depending on the viewing angle of the target structure. On its right, the screen displays the selection of the element ID obtained from the viewpoint, with the selected member highlighted by the blue wireframe line and the unselected part shown by the black wireframe line.

Table 1 displays the results of member detection from multiple viewpoints in the case study, including detection accuracy for each member and overall detection accuracy calculations.

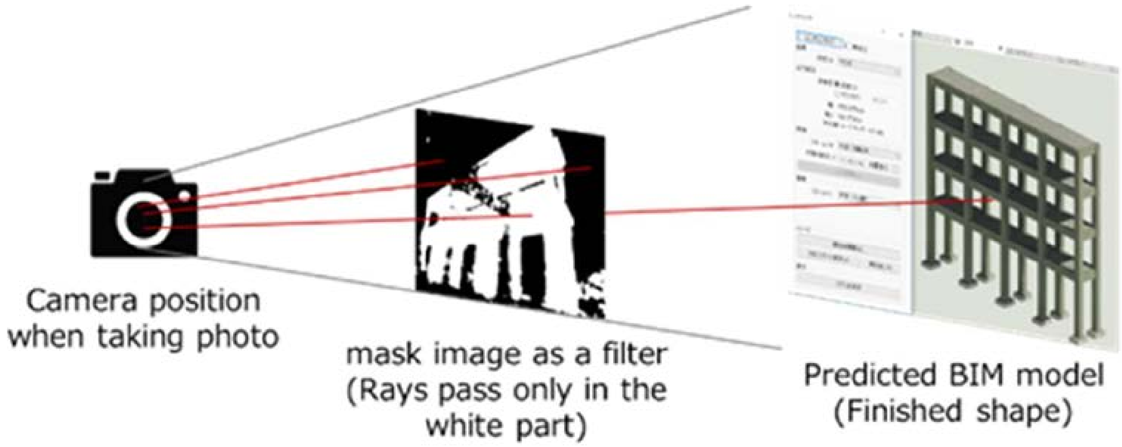

Fig. 5: Image filter in BIM model construction.

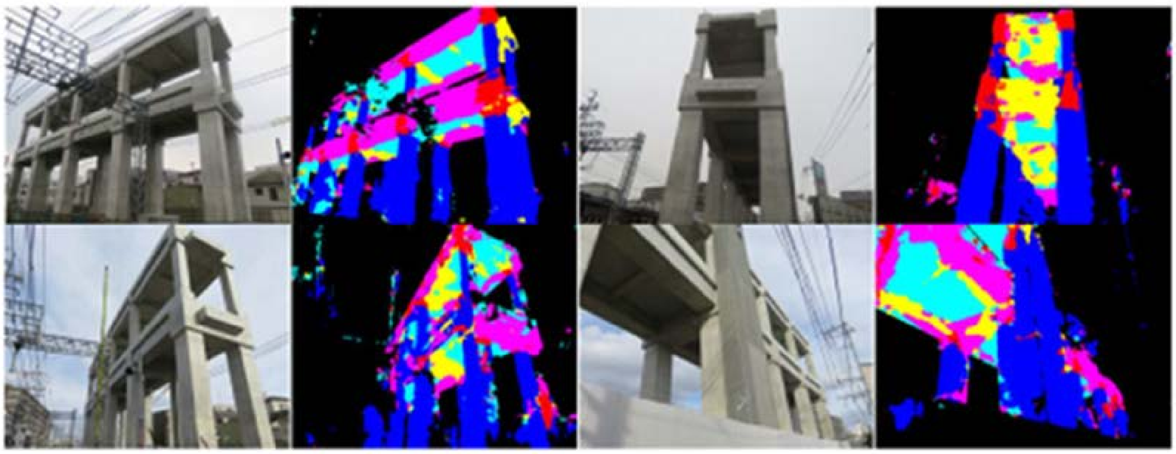

Fig. 6: Part of the results in image processing.

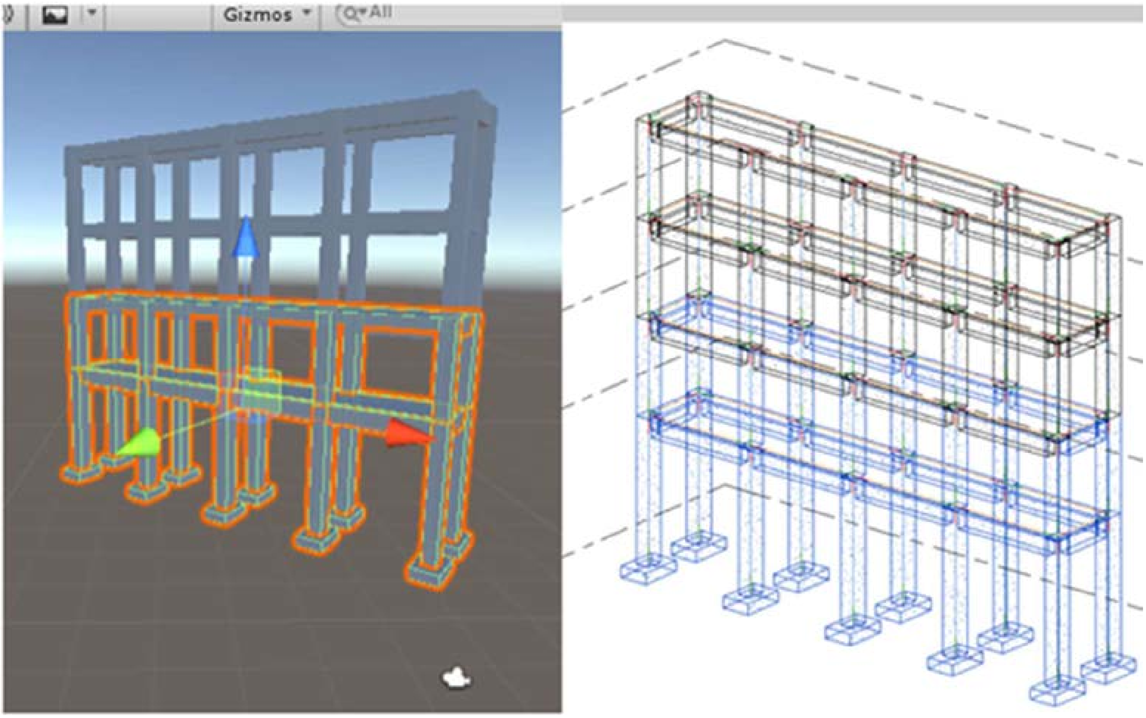

Fig. 7: Generated 3D model in Unity and Revit.

Table 1: Structure member detection accuracy.

Shooting viewpoint	Overall detection accuracy (%)	Column detection accuracy (%)	Floor slab detection accuracy (%)	Foundation detection accuracy (%)	Beam detection accuracy (%)
Viewpoint 1	92.31	100	100	100	80
Viewpoint 2	98.08	95	100	100	100
Viewpoint 3	83.33	90	100	100	75
Viewpoint 4	86.79	90	100	100	80

5. CONCLUSION

This study aimed to verify the effectiveness of using deep learning for detecting structural members and construction equipment at a construction site. To overcome the limitation of existing training datasets, a verification experiment was conducted using images created from photographs of other construction sites. The existing convolutional neural network (CNN) was fine-tuned with different learning weights to detect structural members from actual construction site photos. The following results were obtained:

- The shape of the target structure could be detected from the construction site photographs by considering the detection result image.
- A volume calculation system was constructed using the deep learning model's segmentation results, enabling volume calculation on a three-dimensional model based on the shape information from two-dimensional images.
- The 3D model that reproduces the construction site was displayed on BIM software like Revit by acquiring the element ID from the 3D model using the Unity game engine.

- The recall of the constructed 3D model at each viewpoint showed an average of 90%, demonstrating high accuracy by combining detection results from multiple viewpoints.
- By assigning attribute information of construction unit prices to each member, it was possible to calculate the work volume based on the work form.

To improve the accuracy of the volume detection system, the deep learning model's detection accuracy needs enhancement. The training dataset should include information on detecting obstacles in front of the target. The applicability of the proposed method to other structures and the diversification of the system needs further investigation.

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FIRE SAFETY ENGINEERING: THE COMPUTATIONAL SIMULATION OF THE ESCAPE IN A HISTORIC BUILDING IN BOLOGNA

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ABSTRACT: *In the field of Fire Safety Engineering (FSE), virtual reality has increasingly assumed an important role, especially for the simulation of fire and escape.*

The present work aims at comparing the potential of virtual simulations of the escape of occupants in case of emergency to simulations based on traditional calculations. Above all, the goal is to highlight the greater adherence to reality of the simulations that use behavioural models compared to those that use hydraulic models.

Simulations are performed for the case study of a listed historic tower in Bologna city centre and calculate the Required Safe Escape Time (RSET) in various evacuation scenarios using the innovative Pathfinder® software which, in addition to using flow-based models, is "agent-based", as it manages the variables related to behavioural factors and can model complex escape scenarios faster than hand-made calculation.

Case study results show that RSET times calculated with the behavioural steering mode in the virtual environment are 15-19% higher than the hydraulic mode (SFPE) and therefore demonstrate that the Steering mode is more realistic, as human behaviour significantly influences the evacuation process.

Anyway, all the realistic simulations return safety margin times above 100% of the RSET as asked by national law, highlighting that it is possible to guarantee the safety of the occupants in a particular historical building using innovative Fire Safety Engineering (FSE) approaches, even if the prescriptive rules are not respected.

KEYWORDS: *FSE, Virtual reality, Emergency Escape, ASET/RSET.*

1. INTRODUCTION

Optimizing the fire prevention of a human activity means to identify technical solutions aimed at achieving three primary objectives: the protection of human life, the protection of assets and the protection of the environment. Therefore, in Fire Safety Engineering the chosen escape strategy, i.e., the one that ensures that the occupants can reach a safe location, independently or with assistance, before the fire causes incapacitating conditions, represents one of the most important and most complex designing strategies.

The international legislation as well as the Italian one is increasingly moving from a prescriptive approach (with defined rules to be strictly applied), towards a performance approach with Fire Safety Engineering (FSE) which better allows to deal with the most complex situations.

This new and innovative FSE approach is certainly more suitable for a specific assessment of the individual case under study, and it allows greater flexibility and gives greater autonomy and responsibility to the designer on the basis of rigorous scientific modelling.

Scientific modelling brings a new responsibility to be taken on by the designer and this requires a greater knowledge of FSE processes and having new modelling skills. Virtual reality becomes very important as the scientific-predictive simulation software of the movement of people during the escape manages to model complex escape scenarios and gives data output quickly and efficiently, therefore a better understanding of the phenomenon is achieved even if environmental and specific conditions vary.

The research work under this paper deals with the problem of escape in case of fire in listed historic buildings and in particular compares the results returned by an innovative simulation software with those obtained with other traditional calculation methods.

The case study concerns the museum part of a historic tower in Bologna, the eighteenth-century Astronomical "Specola" Tower, in Bologna, built inside Poggi Palace, which is a historic building listed since 1911. Simulations of the escape were carried out assuming different emergency evacuation scenarios using the Pathfinder® software.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Stefano Tagliatti, Marco Alvise Bragadin, *Fire Safety Engineering: The Computational Simulation of the Escape in a Historic Building in Bologna,* pp. 1125-1136, DOI 10.36253/979-12-215-0289-3.112

In the case of historic buildings, the second objective of fire prevention, i.e., the protection of assets, assumes particular importance and it can be said that among the most complex situations that a designer has to face there are certainly those of protected historic buildings. In these buildings it is very often difficult, or maybe even impossible, to comply with the safety requirements established by the fire regulations due to their particularity or uniqueness and to the constraints to which they are subjected, constraints that are of an artistic, historical, cultural nature and refer both to the building itself and to the context in which it is built. In many cases, the needed structural and MEP renovations could be unsustainable, both in terms of impact and in terms of cost. In fact, many time happens that the minimum dimensions prescribed by the regulations for escape routes are not respected (widths often less than 80 cm, heights less than 1.80 m), or the number of exits is inadequate, or the escape paths (unidirectional and otherwise) are too long, or it is impossible to build external stairs, and so on.

With these situations, for which it is impossible to apply the measures provided for by the national technical rules, it is allowed to turn to the Fire Safety Engineering method (FSE) as considered by the New Italian consolidated Fire Prevention Code (Decreto del Ministero dell'Interno - DM - 2015, 3 August, updated by DM 2019, 18 October) and as presented by the ISO international standards (ISO/TR 13387:1999). Therefore, the designer can use the FSE-based performance approach, which is aimed at the purpose of safety rather than at the rules to achieve it and can apply alternative solutions well-adapted to the specific case that create an equivalent safety level of performance.

Given to the complexity of the application rules of FSE, the support of an escape simulation software such as Pathfinder® is needed. The software application allows the translation of simulation constraints into quantitative values, which can be inserted within a mathematical model of evacuation. In this way, not only the physical and geometric aspects of the structure, but also the qualitative, behavioural and physical aspects of the occupants (children, elderly, disabled, with their own speed and specific decision-making processes, etc.) can be modelled.

2. METHODS

The case study concerns the Specola Tower Museum (Fig.1, 2, 3) which develops entirely inside the tower, from the fourth to the eighth floor (47 m altitude), while the first three floors are included in the structure of Poggi Palace (Fig.1 right). The work involved numerous inspections in collaboration with the museum managers to carry out all the necessary surveys including measurements and identification of all the components of fire safety system.

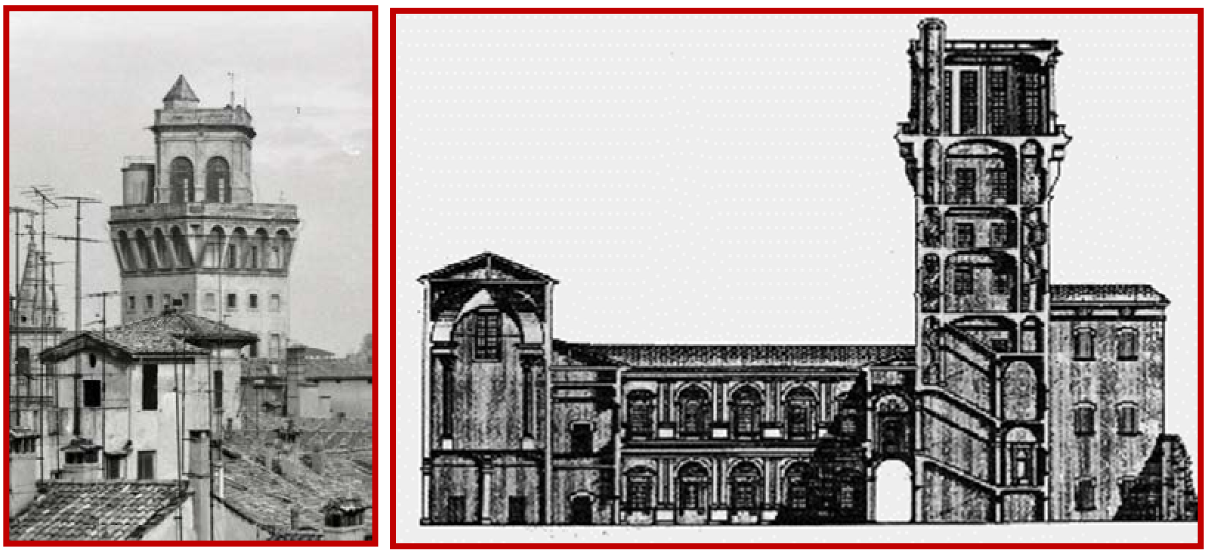

Fig. 1: Picture by Monti P. (1974) of the Specola tower (left) and an 18th century reproduction in section (right)

Fig. 2: Staircases: from the ground floor (left); access to the museum area from the 3rd to the 4th floor (right)

Fig. 3: Spiral staircase from the 4th to the 7th floor of the tower

2.1 The fire safety compliance solution in application of the rules

It should be noted that the New Italian consolidated Fire Prevention Code provides for rules valid for all human-based activities (the so-called "Regola Tecnica Orizzontale" RTO or "Horizontal Technical Rules") and specific rules for historic buildings (the "Regola Tecnica Verticale" or "Vertical Technical Rules" RTV10 and RTV12).

The analysis of the case study was based on the life risk profile, R_{vita} (given by the characteristics of the occupants and the rate of growth of the fire), as well as on the maximum crowding of each room of the structure. The designers found that the rigorous application of the compliance solution for evacuation was not possible, as the prescriptive rules of the Code (RTO) and of the RTV10 specific for museum activities in buildings subject to protection, were not all fulfilled.

• the heights and lengths of escape routes and dead-end corridors comply with the requirements.

• each floor is a specific fire compartment (there are two activities that are not pertinent to each other: museum and offices/services, which are not in separate compartments).

• the stairway area, with annexed landings and corridors, essential for emergency evacuation, is correctly compartmentalized and would constitute a temporary safe area; however, since it is a multi-storey building of considerable height (47 m), the standard requirement is that the current single compartment of the stairwell delimited by REI fire doors is divided into at least three compartments in order to be able to be considered as a temporary safe location (maximum 18 m for the RTV10).

• the width of some horizontal escape routes (Fig.4 on the left) is not compliant with the law (72-73-75 cm, while the limit is 80 cm for the RTV10) and also the width of the spiral staircases (Fig.4 on the right) from the fourth to the eighth floor is not compliant with the law (71-75 cm, while the limit is 80 cm for the RTV10).

• there is only one way out, which, although admitted, is problematic due to the physical characteristics of a part of it, being a spiral staircase, 5 floors long and rather narrow and steep.

compartment	R_{VITA}	width per person (mm/pers)	crowding (persons)	minimum width L_0 (mm)	minimum width (RTV10) (mm)	real width (mm)
4th floor	B2/B1/A2	4.1	36	147.6	800	730
5th floor	B2/B1/A2	4.1	22	90.2	800	820
6th floor	B1/A2	3.8	18	68.4	800	1070
7th floor	B2/B1	4.1	27	110.7	800	850
8th floor	B1	3.6	23	82.8	800	720

compartment	R_{VITA}	width per person (mm/pers)	crowding (persons)	minimum width L_V (mm)	minimum width (RTV10) (mm)	real width (mm)
stairwell (from 4th to ground floor)	B1	2.85	126	359.1	800	820
stairwell (from 5th to 4th floor)	B1	3.1	90	279	800	750
stairwell (from 6th to 5th floor)	B1	3.4	68	231.2	800	750
stairwell (from 7th to 6th floor)	B1	3.8	50	190	800	750
stairwell (from 8th to 7th floor)	B1	4.25	23	97.75	800	710

Fig. 4: Comparison between horizontal (left) / vertical (right) exit widths required by rules and those of the case study.

2.2 The alternative FSE-based solution in application of Section M (Fire Prevention Code)

As the compliance solution is not fully applicable, the designers have switched to the performance approach as proposed by FSE and an alternative solution, provided for by section M of the Code, was proposed to calculate the escape time.

By using the FSE-based performance approach, the designers can propose alternative design solutions that provide an equivalent fire safety level of performance and are sustainable both in terms of architectural and environmental impact and in economic terms.

The alternative solution involves comparing the Available Safe Escape Time (ASET), i.e. the time available for the escape guaranteed by the building, and the Required Safe Escape Time (RSET), i.e. the time actually taken by the occupants for the escape, from the moment the fire is triggered to the moment they reach a safe location to save themselves. The established engineering criterion is that ASET > RSET and that the difference between the two, i.e. the safety margin (t_{marg}), is greater than or equal to 10% of the RSET, and in any case not less than 30 seconds, in the event that the ASET derives from a reliable calculation (obtained by using fire simulation models such as FDS, for example, which is one of the most used software), or is greater than or equal to 100% of the RSET, otherwise. In the case study presented, the reference is the latter, because the ASET was not simulated, but data from examples relating to listed buildings taken from the literature were used.

To calculate the escape time, it is necessary to obtain the RSET time.

The international standard ISO/TR 16738 of 2009 (implemented in the Fire Prevention Code - Fig. 5) defines the RSET as the sum of 4 components:

$$RSET = t_{det} + t_a + t_{pre} + t_{tra}$$

where

- t_{det} is the detection time
- t_a is the alarm time
- t_{pre} is the pre-travel activity time, PTAT
- t_{tra} is the travel time

Of these 4 components, only the calculation of the movement time, Time of travel (T_{tra}), was carried out because the other 3 components of the RSET time are calculated with the European standard (ISO/TR 16738:2009) and were assumed equal respectively to: 60 seconds the T_{det} (*which is considered cautionary since in the museum there is the presence of an automatic fire detection and alarm system-IRAI*), 0 seconds the T_a (as there is an automatic *IRAI with optical-acoustic panels*) and 30 seconds the T_{pre}, which is a low value, because it is due to the *presence of awake occupants, without motor disabilities and trained guides who always accompany visitors to the Museum and who help them with wayfinding*.

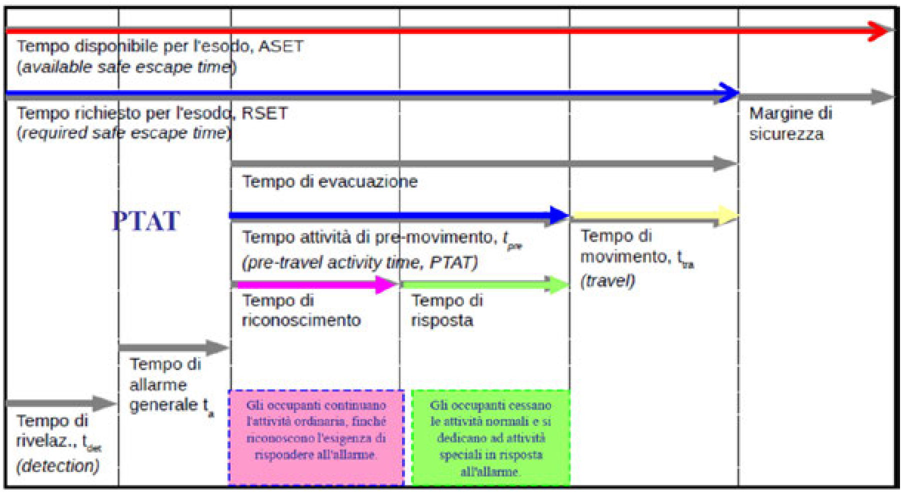

Fig.5 - Comparison between ASET and RSET (Illustration M.3-1 of the Code DM 2019, October 18, modified)

For the calculation of the movement time (t_{tra}) two alternative methods can be used:

1. *flow-based models (hydraulic): they are macroscopic models that represent people as a homogeneous group and in which the movement of the crowd is considered similar to the flow of a fluid.*
2. *ABM agent-based models (behavioural): they are microscopic models that take into account human behaviour, as well as movement, and in which the occupants are considered individually.*

2.3 Escape simulation software and Pathfinder®

Simulation software are essential for the development of behavioural models because they are able to manage a multiplicity of factors: technical, physical and geometric considerations are accompanied by many components connected to the human behaviour of the individual occupants.

These software have been categorized from each other by NIST - National Institute of Standards and Technology (E. Kuligowski, *et al*. 2010) based on the different characteristics: modelling method, model purpose, type of structure, model view of the occupants, behaviour of the occupants, type of movement of the occupants, ability to enter fire data, ability to import CAD data, visualization and validation methods.

The software chosen for the case study is Pathfinder® by Thunderhead Engineering, an agent-based simulator. In addition to being based on the hydraulic models that describe the movement, Pathfinder® manages the behavioural variables, describing complex behaviours and reciprocal interactions. Each occupant is defined by a set of parameters which determines its behaviour during the evacuation phase and the interactions with the other occupants. Pathfinder® is designed to simplify the input phase of the many information managed, but what is more important is that it has *a powerful 3D graphical interface that shows the filmed sequence of the virtual evacuation in a very realistic way.*

Pathfinder® uses a three-dimensional geometry model, however, for simulation purposes, the elements considered are only of the two-dimensional type, to reduce the calculation complexity. The Pathfinder® movement environment (3D continuous space model) is automatically transformed into a 2D navigation triangular mesh (represented by adjacent triangles) on which the occupants are free to move. The use of triangular meshes for the geometric representation allows the software to discretize even curved surfaces quite effectively. Obstacles (up to 1.8 meters away from the floor) are represented in the navigation mesh as empty spaces, which prevent the occupants from being able to move in spaces that house walls, furnishings, objects and therefore in fact they can only move on the navigation mesh. The navigation geometry is organized into irregularly shaped rooms, with boundaries that cannot be crossed by the occupants. The passage from one room to the adjacent one can be done through *connecting doors*. A door that does not connect two rooms and is placed on the outside boundary of one room is defined as an *exit door*. See Figure 6 as an example of a navigation mesh, where occupants are indicated with blue dots, doors with orange lines, and the exit door with a green line. Any mesh zone can be classified as one of four types: open space (room or ramp), staircase, connecting door and exit door, each with a different effect on the occupants' behaviour.

In the user interface, *each person can be assigned their own profile and behaviour*. The profile defines the fixed characteristics of the occupants (i.e., maximum speed, size, colour). The behaviour defines a series of actions that the occupant performs in the simulation (for example moving to a room, waiting time, exiting, route stops). Based on individual characteristics, each occupant makes autonomous decisions on which path to take. It is possible to define groups of occupants with the same behavioural properties who look for each other and who maintain a minimum distance between them (such as families, colleagues, students), associating them with a leader profile (for example a tour guide in a museum).

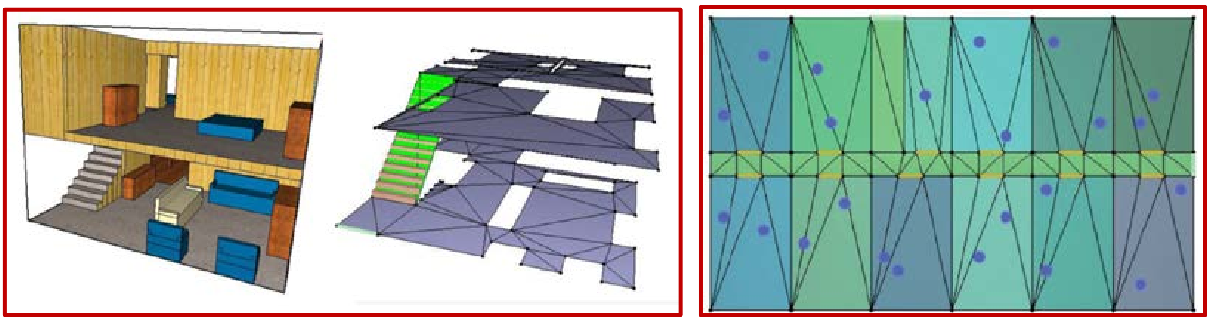

Fig. 6: Example of 3D geometry and related 2D navigation mesh with evidence of rooms, doors and exit doors (Pathfinder Technical Reference Manual, 2022)

Pathfinder® provides two modes of occupant movement simulation:

- *SFPE (hydraulic model)* which reproduces the concepts and calculations defined in the "SFPE Handbook of Fire Protection Engineering, 2016" and in the "SFPE Engineering Guide: Human Behavior in Fire, 2019" and considers the movement of the occupants as a flow model where walking speeds are determined by the density of occupants within each room and flow through doors is dictated by their width. In SFPE mode the occupants do not attempt to avoid each other but may overlap. The main parameters used in SFPE mode are the following: maximum occupant density for the room, effective width of the door (Boundary Layer), specific flow through the doors, movement speed of an occupant.

- *Steering (behavioural model)* which reproduces human behaviour and movement as much as possible and is based on the studies carried out for the first time by C. Reynolds ("Steering behaviours for autonomous characters - 1999"): through a combination of guidance and collision management mechanisms (with people, walls or objects), it allows each occupant to proceed towards his goal while avoiding other occupants and obstacles along the way, proceeding in lanes in the case of counter-current occupants, following other faster occupants, etc. The movements of each occupant in the different possible directions are evaluated and the optimized direction is then determined. The main parameters used in Steering mode are the following: maximum speed of each occupant, maximum acceleration and occupant density.

2.4 The calculation of the T_{tra} with Pathfinder® in the case study

Firstly, *hand calculation* for escape time computation was carried out with a hydraulic model and then Pathfinder® was used to develop the simulations in the two methods provided: SFPE and Steering.

The simulations were carried out to determine how the evacuation time varies according to the different hypothesized scenarios, which differ from each other in terms of the number of occupants, their type and their location.

The working procedure was as follows:

- Setting the geometric characteristics of the building by importing the *3D DWG files* into the software (Fig.7 on the left)
- creation of *5 occupant profiles* (guides, adults, elderly, children and staff) with specific characteristics (travel speed, shape, size, reduction factors, etc.). In Fig.7 on the right the input interface of the "child visitors"
- assignment of a *behaviour* (choice of exit, priority, initial delay, assistance to others, waiting for assistance, etc.) for each profile
- choice of *10 scenarios* (see list in Fig.9):
  - *5 "realistic" scenarios* with 28 occupants (different in type and location), of which 20 visitors admitted at the same time, 2 guides and 6 office workers (in Fig. 8 on the left, the simulation for scenario II in which the mixed visitors - children in yellow, adults in red, elderly people in green and guides in black - they are partly on the 8th floor and partly on the 7th and the office workers, in blue, are all on the 4th floor)

- *1 "theoretical*" scenario with 126 occupants, maximum occupant density admitted by Code (in Fig.8 on the right)
- *4 intermediate "theoretical" scenarios* (with 90, 74, 56 and 29 occupants)

* Calculation of T_{tra} for each simulation with analysis of the speed of the occupants and any critical situation.

10 simulations in Steering mode and 2 in SFPE mode were performed: Fig.9 shows the results obtained.

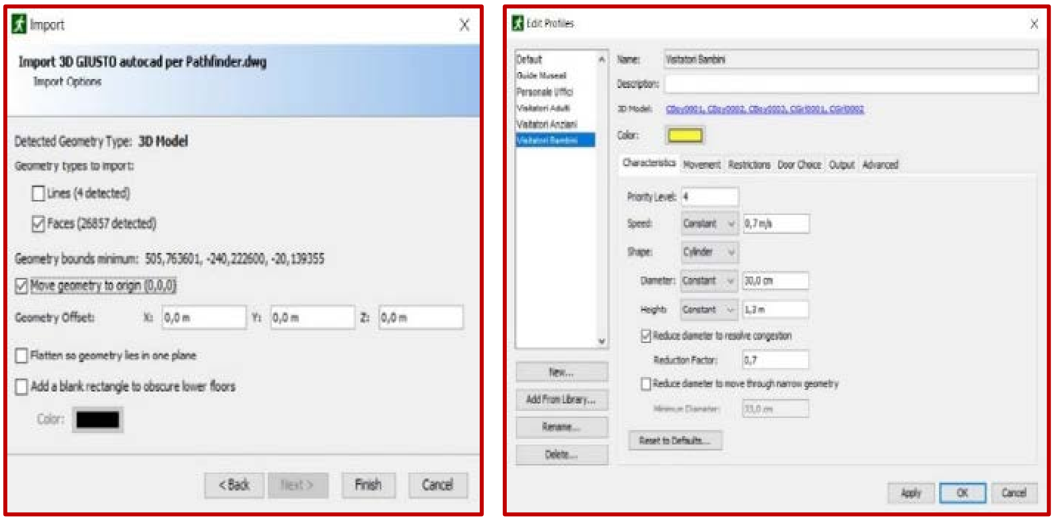

Fig. 7: Pathfinder® user interfaces for importing the 3D DWG file (on the left) and for the characterization of the "Child Visitors" occupants (on the right)

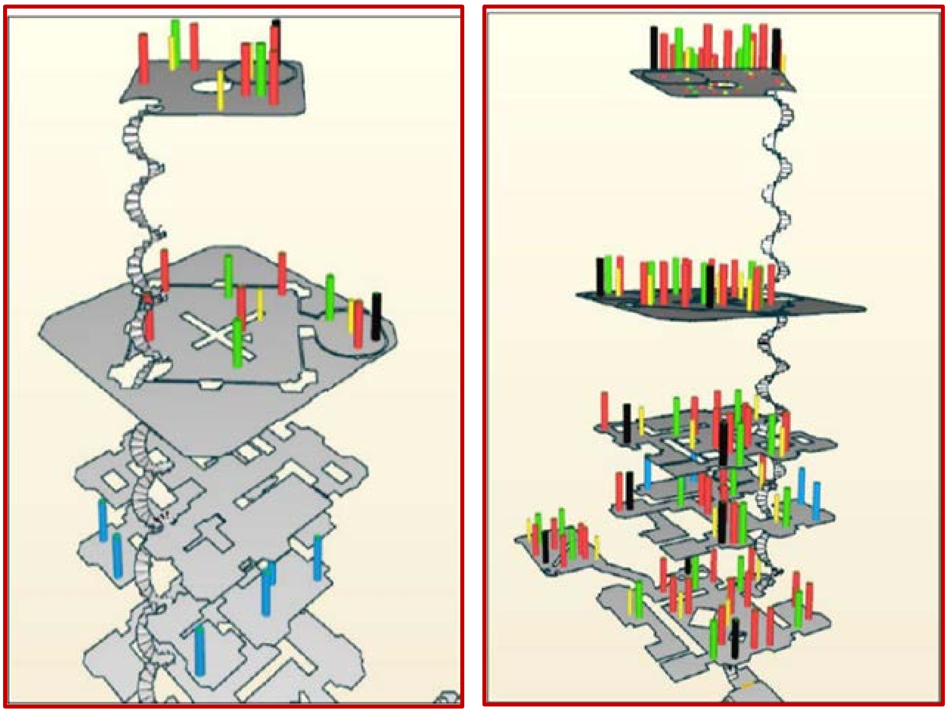

Fig. 8: View of the occupants in simulation II (mixed typology) and in VI (126 people)

The *main outputs* of the software consist of *realistic 3D graphic elaborations and 2D graphics* that allow to reproduce the evacuation and to analyze, even with video still images, any critical situation (queues, high density areas) and the speed of the occupants (see by way of example Fig. 11 and Fig. 12).

Particularly effective in terms of clarity for understanding the phenomenon are the video that reproduce the entire sequence of the evacuation with all its critical points in a very realistic way and with effective times.

scenario (Pathfinder "Steering")		total crowding (persons)	guides (persons)	adult visitors (persons)	elderly visitors (persons)	children visitors (persons)	office workers (persons)	pre-travel time (PTAT) (sec)	travel time (sec)	evacuation time (sec)	RSET (sec)
I	low crowding mixed typology visitors all on the 8th floor	28	2	10	5	5	6	30	272.5	302.5	362.5
II	low crowding mixed type visitors both on the 8th and 7th floors	28	2	10	5	5	6	30	264.5	294.5	354.5
III	low crowding mixed type visitors adults on the 8th floor, others on the 7th	28	2	10	5	5	6	30	241.3	271.3	331.3
IV	low crowding adults visitors only all on the 8th floor	28	2	20	0	0	6	30	219	249	309
V	low crowding children visitors only (or elderly only) all on the 8th floor	28	2	0	0	20	6	30	288.3	318.3	378.3
VI	high crowding mixed typology visitors in all floors (compliant solution)	126	11	55	27	27	6	30	366	396	456
VII	mixed typology visitors as scenario VI except 4th floor	90	8	38	19	19	6	30	355.5	385.5	445.5
VIII	mixed typology visitors as scenario VI except 4th and 5th floors	74	6	31	16	15	6	30	315.8	345.8	405.8
IX	mixed typology visitors as scenario VI except 4th, 5th and 6th floors	56	4	23	12	11	6	30	302.5	332.5	392.5
X	mixed typology visitors as scenario VI only 7th and 8th floor	29	2	11	5	5	6	30	275	305	365
hydraulic hand method	mixed typology visitors as scenario VI only 7th and 8th floor	28	2	10	5	5	6	30	184.3	214.3	274.3
Pathfinder "SFPE" (hydraulic)	mixed typology visitors as scenario VI adults only, 8th floor only	28	2	20	0	0	6	30	181.3	211.3	271.3
Pathfinder "SFPE" (hydraulic)	mixed typology visitors as scenario VI mixed typology on all floors	126	11	55	27	27	6	30	292	322	382

Fig. 9: Escape simulation times processed with Pathfinder® in the case study

3. RESULTS AND DISCUSSION

3.1 Effectiveness of the alternative solution in the case study

The calculations and simulations carried out demonstrate how it is possible to guarantee the safety of the occupants in a particular historical building using alternative measures, even if the prescriptive standards are not respected.

Therefore, it was possible to evaluate the efficiency of the design system and to show that the fire safety measures adopted in the case study are sufficient to guarantee an adequate level of protection of life and assets. All "realistic" simulations, in fact, return safety margins higher than 100% of the RSET time.

It must be said that concerning the case study, an historic tower museum, some important management fire protection measures have been adopted by the museum organization, that help to increase the safety margin, reducing the RSET:

- the non-simultaneity of the two activities carried out inside the building (museum and offices/services).
- the limitation of the maximum crowding of museum visitors, divided in no more than two groups (one for each of the two museum guides).
- the ineligibility of visitors with motor disabilities.
- the access of visitors only accompanied by properly trained guides, who lead people who otherwise would not be familiar with the place.

In addition to these safety measures, an important role is played by the preventive and protective measures adopted by law, i.e. the presence of an automatic fire detection and alarm system (IRAI); the entire active protection system for extinguishing the fire (fire extinguishers and internal fire hose reels) built in all the museum spaces; a clear signal that facilitates the wayfinding process; the compartmentation of the escape routes (staircases and corridors on the ground floor) open to the public, with the insertion of suitable REI fire doors; the limitation of the fire loads in these paths (because of this they can be considered as temporary safe locations). In consideration of the above fire protective measures, it can be said that the overall safety is excellent, as the horizontal paths in the various floors are very short.

However, as already mentioned, the ASET time taken as a reference would require a more precise calculation using fire simulation models, i.e., deterministic models based on the principles of physics and chemistry. For this reason, in this study, a safety margin equal to 100% of the RSET was always considered, as required by the international and local regulations. Furthermore, again to play on the safe side, not all the management fire protection measures mentioned above and actually adopted, were considered as present in the simulations.

3.2 Utility of the escape simulation software

The simulations (Fig.9) show that the movement time obtained with the SFPE mode (181.3 sec) is more or less equivalent with the one obtained with the hand calculation with the hydraulic model (184.3 sec). Therefore, using the software in SFPE mode, which uses the hydraulic model, there is no significant qualitative improvement of the results compared to the hand calculation, but only a greater computing speed.

The simulations carried out with the Steering (behavioural) mode, on the other hand, show a significant difference compared to the simulations in SFPE mode (hydraulic model). It emerges, in fact, that the calculated times are 15-19% higher than those of the SFPE mode. This occurs because the SFPE mode admits the physical overlapping of the occupants in the queues that form in the exits and does not properly consider the interactions between the occupants themselves, which makes this mode clearly less adherent to reality (see Fig.10).

Fig. 10: Occupant overlay at stair entrance using Pathfinder® SFPE mode

Furthermore, with the behavioural steering mode, some critical situations clearly emerge which strongly affect escape times. Queues are created in emergency escape and gatherings near the access sections from the floors to the stairs, i.e., at the intersection (so-called "converging nodes") between the evacuation flows of the occupants who come from the floors and those who come from the spiral staircases. This demonstrates how the Steering mode is much more realistic, as human behaviour significantly influences escape times. The Pathfinder® software has various ways of representing these critical situations. Firstly graphs with the progression of the evacuation (Fig. 11 on the left) and secondly the flow rates in the reduced access sections (Fig. 11 on the right); then the 3D graphic elaborations with crowding densities (Fig. 12 on the left) and the graphic elaborations that represent the so-called Level of Service (LoS), that is the criticalities in the queues, in the walkways, and in the movement on the stairs (Fig. 12 on the right).

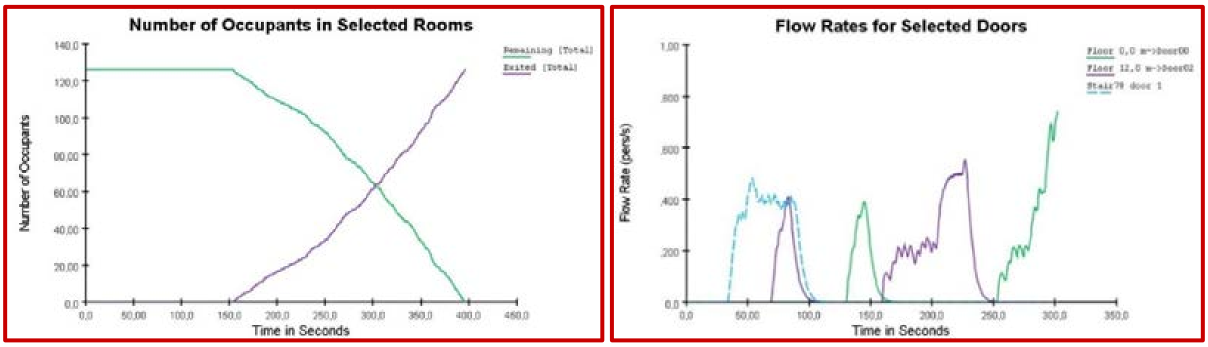

Fig. 11: escape simulation times in scenario VI (left); flow rates at the significant gates in scenario I (right)

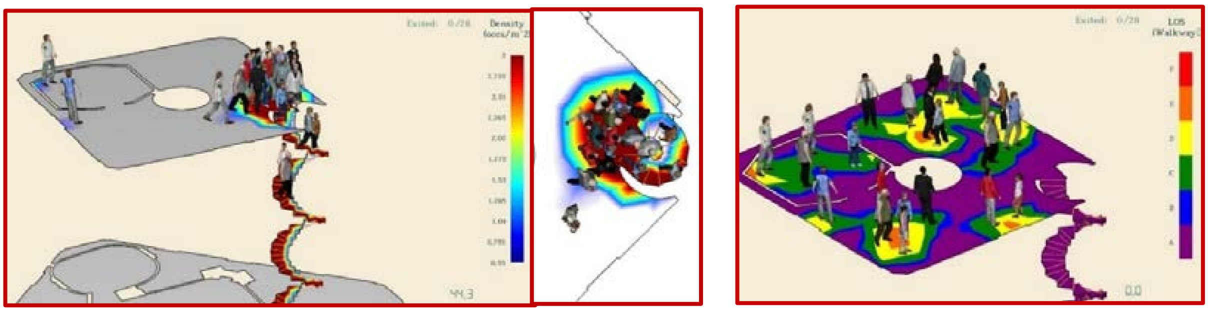

Fig. 12: Scenario I - on the left occupant density in the critical section of the stairwell at the exit of the 8th floor - on the right Service level (Walking LoS) in the most critical location on the 8th floor

These simulations also show that the presence of visitors with reduced travel speed (children and the elderly) strongly limits the evacuation from the building (times longer by about 30%, as shown by the comparison between scenarios IV and V - Fig.9).

Even the most critical simulation among the realistic ones (scenario V - school group of 20 children all on the 8th floor) appears to be in compliance with the prescription of the alternative solution of the FSE (safety margin must be greater than 100% of the RSET). The comparison of the assumed ASET and RSET gives as results the following equation:

$$ASET - RSET = 106\%\ RSET.$$

For the sake of completeness, an unrealistic hypothesis was also developed. This hypothesis foresees the maximum crowding allowed by the compliant solution, equal to 126 total occupants (scenario VI). In this case, due to the numerous queues and gatherings that are created above all on the 6th and 7th floors in the access door to the stairwell, the criterion provided for by the Code is not respected, but there is still a wide time margin:

$$ASET - RSET = 71\%\ RSET.$$

Another interesting evaluation uses simulations IX and X in order to estimate the maximum crowding which allows, with the assumed scenarios, compliance with the criterion t_{marg} = 100% • RSET = 390 seconds. The number of occupants is obtained by interpolation of the linear function referred to the two simulations IX and X and is equal to an estimate of 54 people (see the graph in Figure 13).

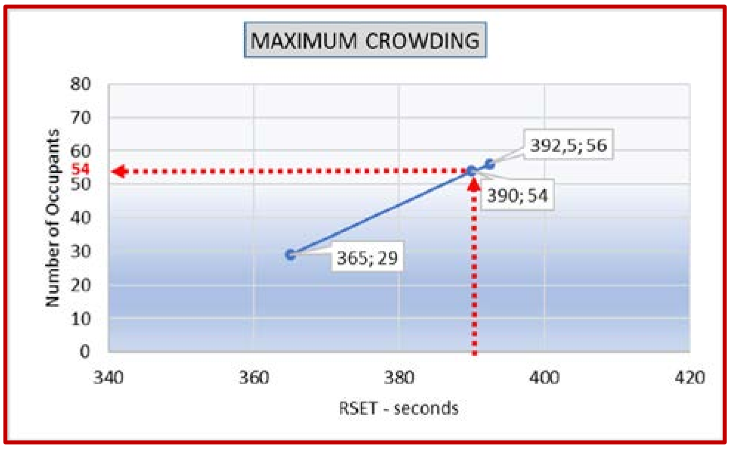

Fig. 13: Estimate of maximum crowding using the escape simulation times of scenarios IX and X

In Figure 14 there are two screen shots of the VI simulation with 126 occupants, taken from the video made with the simulation software, which shows the entire evacuation and gives an idea of the power of virtual representation of reality that Pathfinder® has.

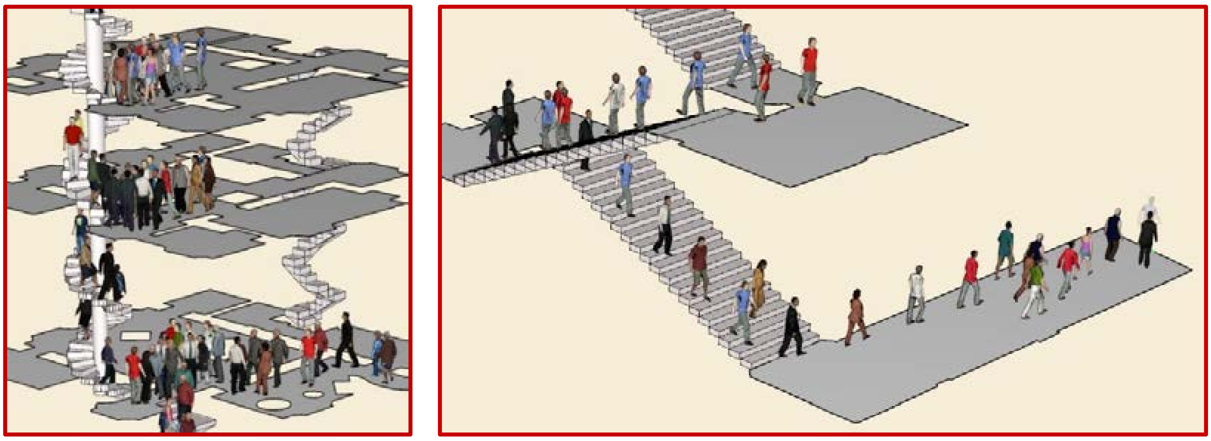

Fig. 14: Examples of 3D graphic visualization of the occupants in the escape simulations processed with Pathfinder® (Steering mode) in the case study

4. CONCLUSIONS

The most innovative escape virtual modelling software, such as Pathfinder®, are able to return high-quality results by means of video based visualization techniques that perfectly simulate reality and give an absolutely real perception of what can happen in the hypothesized situation. This software is used as a planning tool of the evacuation dynamics of an environment and allows to explore different evacuation cases and scenarios, varying the parameters of the simulation and the properties of the occupants. This makes possible to calculate the evacuation times in the various scenarios and to highlight the most critical ones.

The research work under this paper clearly shows hydraulic models are less in adherence to reality than behavioural models that are more reliable by using a scientific-predictive simulation software of the movement of people during the escape such as Pathfinder®.

Behavioural models are able to demonstrate how human behaviour significantly influences evacuation times and are able to give quantitative outputs, evaluated from a series of assigned parameters.

Due to their greater flexibility, these software bring out critical issues that otherwise could not be considered in the fire safety design phase, as for example delays in time due to congestion and queues in areas of restriction or intersection of multiple flows.

Anyway, the use of virtual simulation requires new skills and greater caution, as they are highly sensitive to some input parameters, but they contribute to a better understanding of the phenomena as they give quickly new results with the variation of the individual conditions.

Due to their characteristics, they can therefore also be of great use for simulating the evacuation of occupants in other emergency situations, such as earthquakes, terrorism or other cases in which people's safety is threatened.

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QUANTIFYING THE CONFIDENCE IN MODELS OUTPUTTED BY SCAN-TO-BIM PROCESSES

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ABSTRACT: *3D spatial data is increasingly employed to generate Building Information Models (BIMs) by extension digital twins for various applications in the architecture, engineering, and construction (AEC) sector such as project monitoring, engineering analyses, retrofit planning, etc. The outputted models of Scan-to-BIM processes should satisfy pre-defined levels of quality. In the case of emerging automated Scan-to-BIM solutions, users however currently need to check all generated geometry manually, which is time-consuming. What would help users is if the automated systems could also provide a level of confidence in the detection and modelling of each element. In this paper three generic indicators are defined for analysing the reliability of the generated 3D models:* $I_{coverage}$ *estimates the portion of the surface of the modelled element that can be explained by the input point cloud.* $I_{distance}$ *defines the closeness of the generated element models to the input point cloud. The confidence of the generated 3D local models can be computed by combining the two aforementioned indices. The proposed indicators are assessed using actual examples and comparisons are conducted between automatically generated 3D BIM models and 3D models generated manually by a BIM modeler.*

Keywords: *BIM, point cloud, confidence, indoor modelling, wall, digital twin*

1 INTRODUCTION

Digital twinning of built environment assets is a modern data-driven process with benefits to improving performance and productivity within the Architecture, Engineering, and Construction (AEC) industry. It affords a multi-dimensional view of how an asset will perform by simulating, predicting, and making decisions based on real-world conditions (Boje et al., 2020). At the information (or data) level, it represents the information in a useful, structured form of description. At a higher level, it applies tools that make use of that information to provide diagnostics of why something might be happening, predict the possible future outcome, and decide the action based on the objectives. Optimising construction project execution (Akula et al., 2013; Bueno et al., 2018), building energy usage (Valero et al., 2021), and space utilization (Pan et al., 2022) are some of the numerous use cases of digital twins in the built environment. A built environment digital twin is commonly built from a Building Information Model (hereafter `BIM model'), which contains geometric and some semantics (such as element materials) that can be used to support the envisioned use cases (I. Giannakis et al., 2015).

The generation of BIM models of new buildings is done during the delivery process with an as-design BIM model created during the design phase that should then ideally be updated into an as-built BIM model that incorporates any change made during construction. But, BIM models also increasingly need to be created for existing buildings, for example to plan refurbishment or enhance operation.

In a 2020 survey conducted in 78 countries 2020, professionals asserted major benefits that BIM brings to the construction process from a geometric viewpoint (Rocha et al., 2021). However, the generation of BIM models is challenging due to the complexity and diversity of building geometry, and the possibly high levels of clutter existing in occupied buildings. New technologies, such as Terrestrial Laser Scanners (TLS) or photogrammetry (PG), now enable the acquisition of dense and accurate 3D geometric data, in the form of point clouds. Scan-to-BIM is the process to produce the as-built model of an asset from laser scanned or photogrammetric point clouds (Bassier & Vergauwen, 2020; Bosché et al., 2015a). It includes segmenting the data and generating a final semantically-rich 3D model (Rashdi et al., 2022). Despite the benefits afforded by those new sensing technologies, the generation of BIM models remains challenging due to the complexity and diversity of building geometry, and the possibly high levels of clutter existing in occupied buildings.

Although Scan-to-BIM is generally a manual process in current industrial practice, there is extensive research in academia and industry to develop automatic Scan-to-BIM algorithms (Nikoohemat et al., 2019; Thomson & Boehm, 2015; Valero et al., 2021). For example, a Scan-to-BIM solution based on deep learning is developed in (Perez-Perez et al., 2021) for semantic segmentation. It classifies beam, ceiling, column, floor, pipe, and wall elements using two convolutional neural network and one recurrent neural network.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Shirin Malihi, Frederic Bosche, Martin Bueno Esposito, *Quantifying the Confidence in Models Outputted by Scan-To-BIM Processes*, pp. 1137-1146,

Some researchers (Bassier & Vergauwen, 2020) have gone beyond the problem of object detection in scan-to-BIM, and presented results producing BIM models in IFC from semantic information extracted from point clouds (IFC is an open data schema described as in ISO 16739-1:2018 (BuildingSMART, n.d.)).

However, (Rocha et al., 2021) reported that Level of Accuracy was used in 9.2 % of the research reviewed from the literature, which shows a big room for development and using this concept. Guaranteeing the completeness and accuracy of BIM models generated through Scan-to-BIM processes (manual or automated) is an important issue. In previous research, authors have mainly done this manually. For example, in (Skrzypczak et al., 2022) the authors compare the lengths from total station measurements and the BIM model generated from Scan-to-BIM approach. But, comparisons like this are established to check quality manually for the purpose of academic assessment.

In practice, however, the user would need to know to what extent it can be confident that a scan-to-BIM algorithm has produced a correct model from the input point cloud data. Without any such information, the user will need to check every reconstructed element against the input data and gauge correctness manually, which is a time-consuming, and error-prone process that partially undoes the benefits afforded by automated scan-to-BIM algorithms.

Reducing this manual work could be achieved if the scan-to-BIM algorithm could also report some level of confidence for the modelling of each element in the outputted model. In this paper, we explore two such generic metrics (and a third one combining them) to automatically assess the quality of the model generated by a Scan-to-BIM algorithm, focusing on geometrical fitness.

The proposed indicators of the confidence are introduced in section 2. Section 3 then reports experimental results on their evaluation using some real case studies. Finally, the results are discussed and avenues for future work suggested in Section 3.

2 METHOD

This section presents the method proposed to calculate the level of confidence in BIM models outputted by Scan-to-BIM processes. Two different indices are defined $I_{coverage}$, $I_{distance}$, and *their combination* that can be computed for any element in the outputted model. They are detailed in the following sub-sections.

2.1 $I_{coverage}$

$I_{coverage}$ is the principal index and aims to capture how much of the modelled 3D surface of a given element in the outputted model is explained by the input point cloud data. One quantitative measure of this consists in homogeneously discretizing the element's surface and check if some points from the input point cloud lay in the neighbourhood and describe that discrete surface.

A practical way to implement this is to use space voxelization. First, for each modelled element, a voxelization is performed in its bounding box, with a resolution δ (e.g. $\delta = 2.5$cm). The set of voxels intersecting the element mesh is then found (we use the method described in (Open3D)); we call this set γ_m . Then, we identify the subset of voxels in γ_m that also contain points from the point cloud. Points are searched inside the voxels. The centre of each voxel is the base of this search. KD tree structure is used to partition this space and efficiently search the set of points falling within each voxel. We call this second set γ_c. We then define $I_{coverage}$ as:

$$I_{coverage} = \frac{|\gamma_c|}{|\gamma_m|} \tag{1}$$

where $|.|$ is the cardinality operator. $I_{coverage}$ takes values between 0 and 1, with 1 indicating that the entire surface of the element’s mesh has matched scanned point in its vicinity, i.e. within δ distance.

2.2 $I_{distance}$

$I_{coverage}$ captures how much of the modelled surface is explained by a point cloud in a somewhat coarse way, and considers neither how closely the modelled surface matches the point cloud nor the local orientation of the points and the modelled surface. The metric $I_{distance}$ aims to complement $I_{coverage}$. For this, we take the set of point cloud that are in the voxels in γ_c (called n), calculate their closest (orthonormal) distance to the element mesh, and then compute $I_{distance}$ as follows:

$$I_{distance} = \frac{1.0\,.n_1 + 0.5\,.n_2 + 0.25\,.n_3 + 0.125\,.n_4 + 0.0625\,.n_5}{n} \tag{2}$$

where n_1 is the number of the n points that are within $\left({}^{1}\!/_{5}\right)\delta$ distance to the mesh, n_2 is the number of the n points that are between $\left({}^{1}\!/_{5}\right)\delta$ 1 and $\left({}^{2}\!/_{5}\right)\delta$ distance to the mesh, n_3 is the number of the n points that are between $\left({}^{2}\!/_{5}\right)\delta$ and $\left({}^{3}\!/_{5}\right)\delta$ distance to the mesh, n_4 is the number of the n points that are between $\left({}^{3}\!/_{5}\right)\delta$ and $\left({}^{4}\!/_{5}\right)\delta$ distance to the mesh, and finally n_5 is the number of the n points that are between $\left({}^{4}\!/_{5}\right)\delta$ and δ distance to the mesh.

Calculation of the distance between a point of the point cloud and a triangle of the mesh satisfying two conditions that are the projection of the point on the plane, formed by the triangle, should be located inside this triangle, and additionally the distance between the point and the mesh triangle should be less than the buffer size. Afterwards points inside this buffer are used to compute the $I_{distance}$ using the weighted average formula in Equation 2. $I_{distance}$ also takes values between 0 and 1, with 1 indicating that all the points are very close to the mesh (within $\left({}^{1}\!/_{5}\right)\delta$ distance).

3 EXPERIMENTAL VALIDATION

The validation of the proposed method is conducted using an example Scan-to-BIM algorithm, but the method is applicable to the use of any other algorithm. The employed Scan-to-BIM solution was developed as part of the EU-funded Horizon2020 BIMERR project (Valero et al., 2021). The whole solution is semi-automatic and aimed at producing as-is models that contain as much information as possible to support the efficient (automated) development of an energy model that can be used to conduct simulations for refurbishment planning. This solution is divided into three components (Valero et al., 2021):

1. The *Structural Scan-to-BIM* component that automatically generates an IFC model containing the main architectural elements (floors, walls, openings, spaces) as well as second level space boundaries;
2. The *Mechanical, Electrical and Plumbing (MEP) Scan-to-BIM* component that automatically enriches the IFC model with elements such as radiators, HAVC units and sockets (Bosché et al., 2015b); and
3. *Scan-to-BIM Editor* to manually enrich the model with wall layers, materials, material properties and MEP properties.

The modelling confidence metrics proposed herein could be employed in each component, but are assessed here in the context of the first component of the solution, the Structural Scan-to-BIM component.

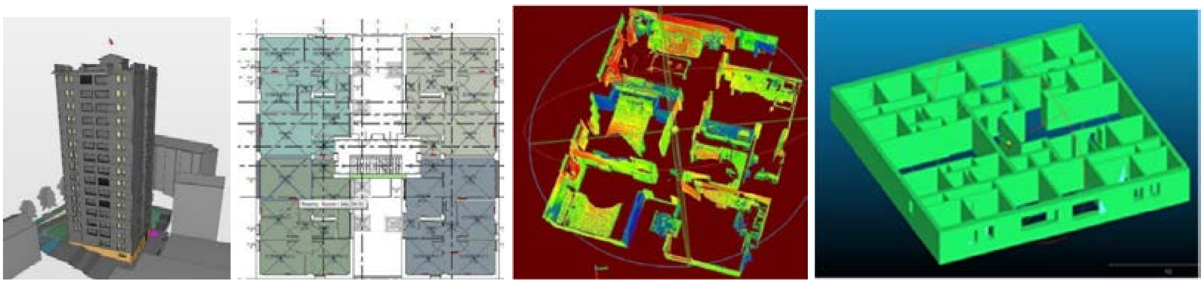
3.1 Experimental Data

One of the pilot sites of the BIMERR project is the two-story Kripis House located in Thessaloniki, Greece. A coloured point cloud of the whole house (exterior and interior) was captured using a terrestrial laser scanner Faro Focus 150s, and subsequently subsampled to a density of 1 pt/cm^2.

This house is furnished, however the interior is not much cluttered. The *Structural Scan-to-BIM* component automatically delivered a 3D model of the house in IFC format from that point cloud alone. A second pilot site is located in Bilbao, Spain. This is a multi-story apartment building, with essentially the same layout on all floors. Each floor contains four flats. A storey of the building was captured fully by terrestrial laser scanning. In contrast to the Kripis House, the Bilbao environment is cluttered because the building was scanned when fully inhabited. It contains wardrobes cupboards and other pieces of furniture and personal belongings inside rooms, resulting in significant levels of occlusion, which challenge Scan-to-BIM processes.

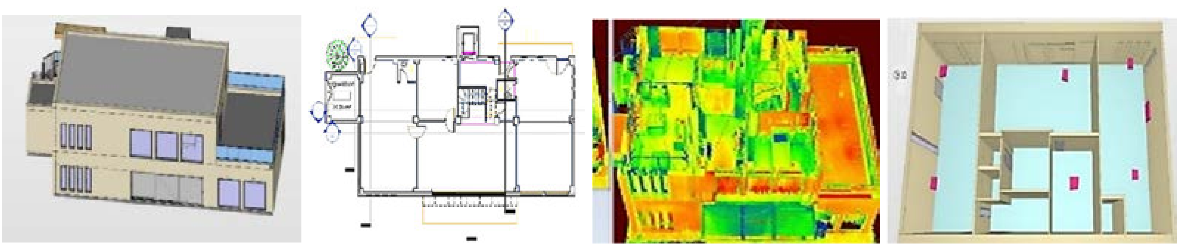
To assess the value of the proposed confidence metrics to report Scan-to-BIM confidence levels, manual scan-to-BIM was conducted by architects using standard commercial software and the resulting models exported in IFC. While those models may contain errors, they are generally good and can serve as ground truth. The validation then focuses on the walls, as walls are the most frequent elements in the models. The walls modelled manually and with the automated process are compared.

Figure 1 shows the Spanish dataset and the corresponding output IFC model generated by the *Scan-to-BIM* tool. Figure 2 shows the same information for the Greek dataset.



(a) (b) (c) (d)

Figure 1 : Spanish dataset and Scan-to-BIM output. The 3D model generated manually by the BIM modeller (a), plan view of one floor (b), the point cloud of one apartment (c), and 3D IFC model outputted by the Scan-to-BIM component for one floor (d).



(a) (b) (c) (d)

Figure 2: The 3D model generated manually by the BIM modeller (a), plan view of one floor (b), the point cloud (c), and 3D model outputted by the Scan-to-BIM (d). Stuff of indoor spaces are displayed in the point clouds.

3.2 Results and Discussion

First of all, we report on the overall wall detection performance of the Scan-to-BIM component. In an IFC model, correctly detected walls are counted as true positive (TP), non-existing detected walls are counted as false positive (FP), and missing walls are counted as false negative (FN).

Table 1 summarizes the performance obtained by the automated Scan-to-BIM algorithm. The results bring to light the challenges faced in the case of the Spanish dataset. While the automated Scan-to-BIM tool detected most walls (despite the clutter, noise and furniture of the rooms) but many walls modelled by the tool that actually do not exist, and four walls missed. In the case of the Greek project, 100% recall is achieved and 96% precision. Two FPs are reported, but these include a protruding beam confused as a wall and two columns modelled as a wall. These can in fact be considered acceptable because the automated Scan-to-BIM algorithm assumes that the structure of residential buildings is composed of walls and slabs only, and thus does not explicitly look for and model columns and beams.

Table 1: Wall detection performance of the Scan-to-BIM tool.

	TP	FP	FN	Recall	Precision
Spain dataset	60	14	4	94%	81%
Greece dataset	45	2	0	100%	96%

Figure 3 and Figure 4 show some of the modelling errors made by the automated algorithm with both datasets.

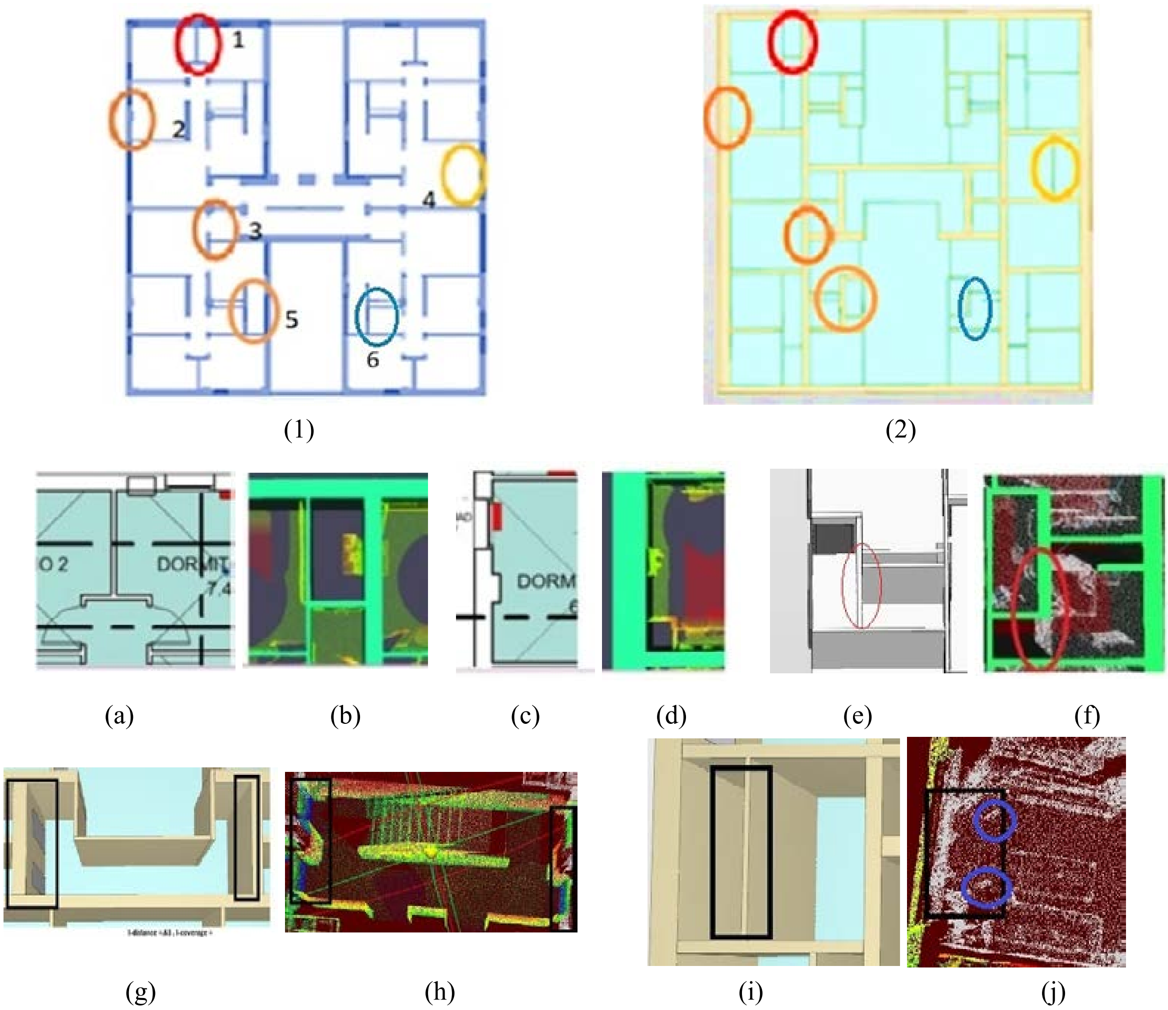
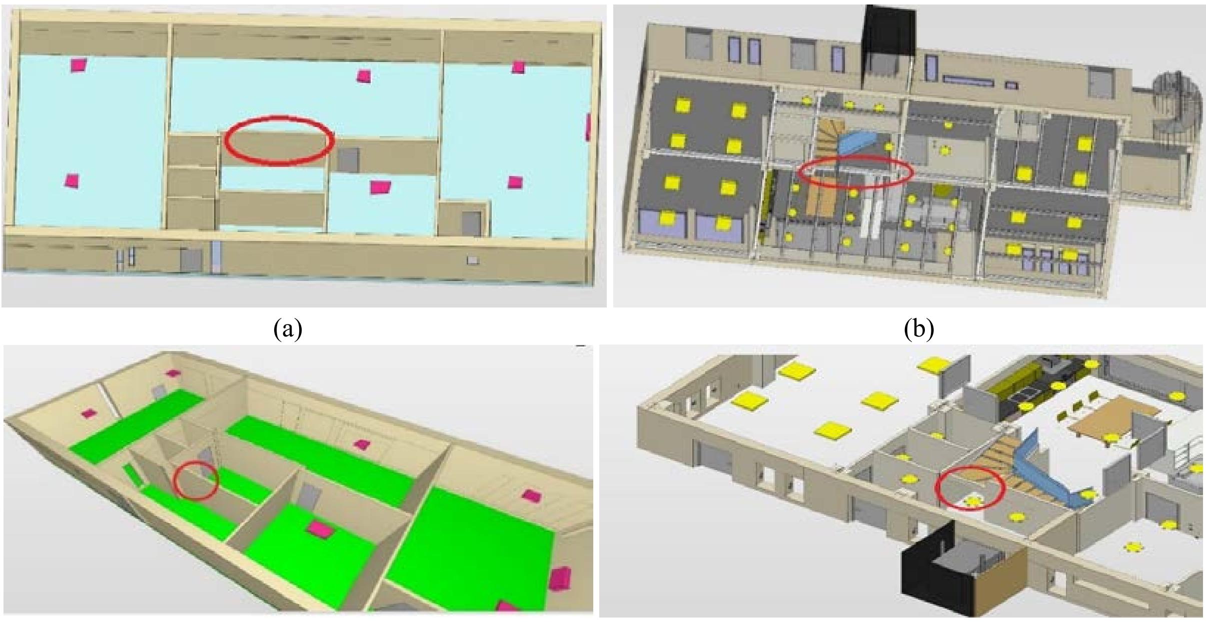


Figure 3: Modelling errors in the Spanish dataset. Errors in the manually-generated BIM model and the automated Scan-to-BIM algorithm are shown in (1) and (2) respectively. (a) and (b) show a wall which is modelled as a room with walls due to the presence of wardrobes inserted in the spaces on both sides. (c) and (d) depict a wall which is modelled as thick the column that is embedded in it. (e) and (f) demonstrate FN wall examples. (g) and (h) display an error in the modelling of thickness of walls. (i) and (j) show FP walls due to clutter in the room near the wall.

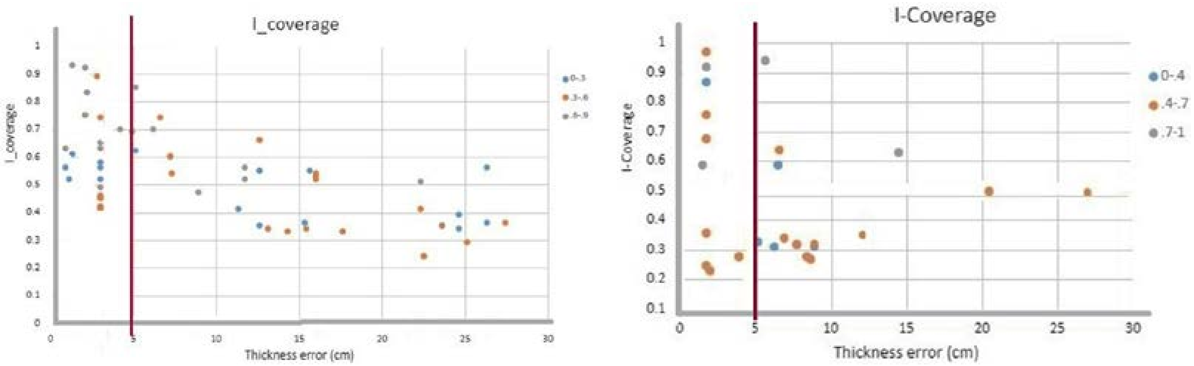


(a) (b)

(c) (d)

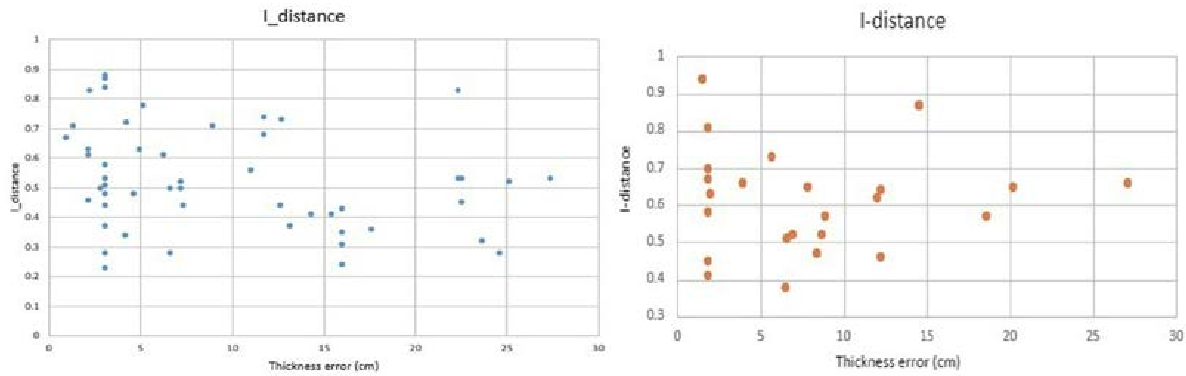
Figure 4: modelling errors in the Greek dataset. (a) and (c) show the model generated by the automated algorithm, while (b) and (d) show the model generated manually. In (a) and (b) a wall is modelled instead of two columns and a beam. (c) and (d) show a wall modelled instead of a beam.

Figure 5 reports the $I_{coverage}$ values obtained for each wall in the Spanish and Greek datasets. This figure plots the $I_{coverage}$ against the difference between the thicknesses of a given wall modelled manually (ground truth) and the same wall modelled automatically by the Scan-to-BIM algorithm. Note that in this experiment we use δ = 2.5 cm. The red vertical lines in Figure 5 are inserted on the distance of 2δ . This line is important because, if the wall is modelled at the right location but with a thickness error larger than 2δ, than the number of points within δ of each wall side, and a result the value of $I_{coverage}$ should be much lower. Figure 6 shows the $I_{distance}$ against the wall thickness error for the two datasets.



(a) (b)

Figure 5: $I_{coverage}$ and thickness errors for two datasets of Spanish (a) and Greek (b). They are coloured based on their corresponding $I_{distance}$ and split into three groups. The red vertical lines are inserted on the distance of 2δ.

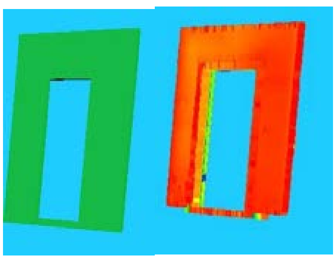


(a) (b)

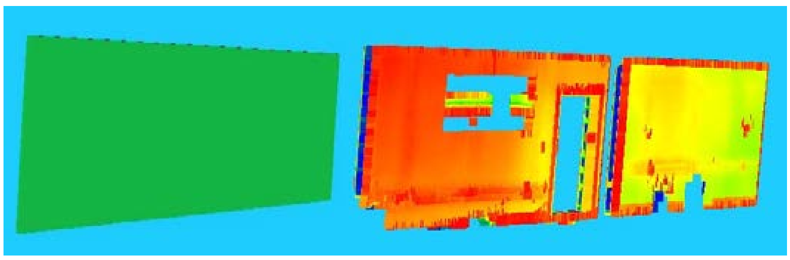
Figure 6: $I_{distance}$ and thickness errors for two datasets of Spanish (a) and Greek (b).

Looking at Figure 5, one can see a trend where $I_{coverage}$ is lower for walls with greater thickness error (in particular $>2\delta$). This implies some correlation between $I_{coverage}$ and the confidence in the modelling quality. Nonetheless, some outliers do exist and good confidence seems to be only achieved for very high values of $I_{coverage}$ For $I_{distance}$ (Figure 6) a similar, but less positive trend can also be observed, as more obvious outliers can be observed.

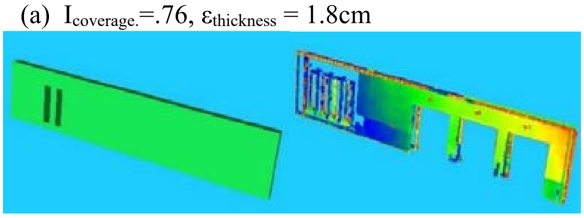
Figure 7 shows coverages and thickness errors of seven sample walls which were selected from different parts of Figure 5. (a, b) show examples where $I_{coverage}$ >0.5 and thickness error < 2δ. (c, d) show example for which $I_{coverage}$ is lower with values closer to 0.5, with one wall having thickness error >2δ and the other just below 2δ. The average value of $I_{coverage}$ in both cases are due to the fact that one of the faces of the walls is detected correctly, but the other one is wrongly detected. In the case of (c) this is due to a structural column (which the algorithm fails to detect) that leads to a gross over estimation of the width of the wall which subsequently leads to only very few points being matches to that face of the wall. The two large undetected windows also impact $I_{coverage}$. In (d), the second face of the wall is also wrongly modelled because the algorithm wrongly selected the curtains as the boundary for that wall. This results in lower (although not insignificant) thickness error which is still high enough to impact $I_{coverage}$. The conclusion is that, in both cases, $I_{coverage}$ rightly represents some level of error (for one face of the walls). (e, f) show walls for which $I_{coverage}$ <0.5 and thickness errors > 2 δ. These walls similarly have one face of the wall that is wrongly modelled, which is the source of the thickness error and implies that $I_{coverage}$ couldn't be higher than 0.5, as in the examples (c, d). But, (e, f) additionally contain undetected large windows and many occlusions due to desk, frame and mirror. Finally, (g) shows a wall that has a very low $I_{coverage}$ value (0.23) despite a small thickness modelling error. This may first appear to show a weakness of the proposed $I_{coverage}$ index. But, actually, in this case, while the wall is modelled with only 2cm thickness error, both faces of the wall are wrongly modelled and the wall end up looking like it was modelled at a location 4cm away from its true location. Therefore, $I_{coverage}$ rightly responds to this important modelling error.



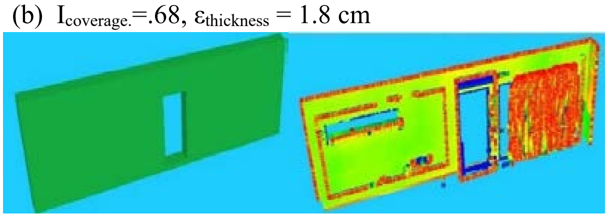
(a) $I_{coverage.}$=.76, $\varepsilon_{thickness}$ = 1.8cm



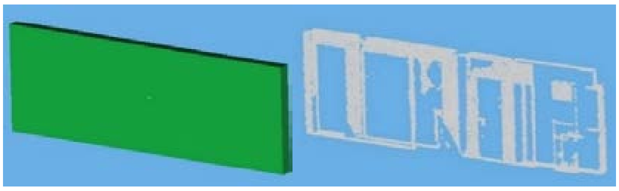
(b) $I_{coverage.}$=.68, $\varepsilon_{thickness}$ = 1.8 cm



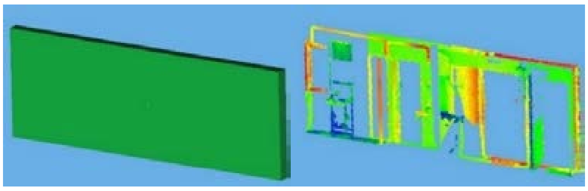
(c) $I_{coverage.}$=.51, $\varepsilon_{thickness}$ = 27.1cm



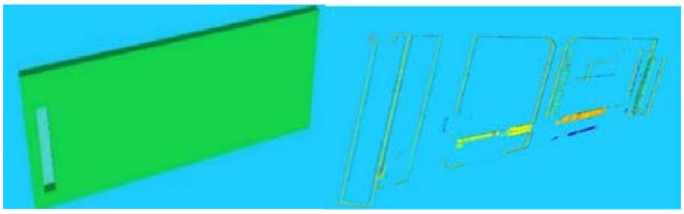
(d) $I_{coverage.}$=.63, $\varepsilon_{thickness}$ = 4.5 cm



(e) $I_{coverage.}$=.41, $\varepsilon_{thickness}$ = 11.3 cm



(f) $I_{coverage.}$=.35, $\varepsilon_{thickness}$ = 12.6 cm



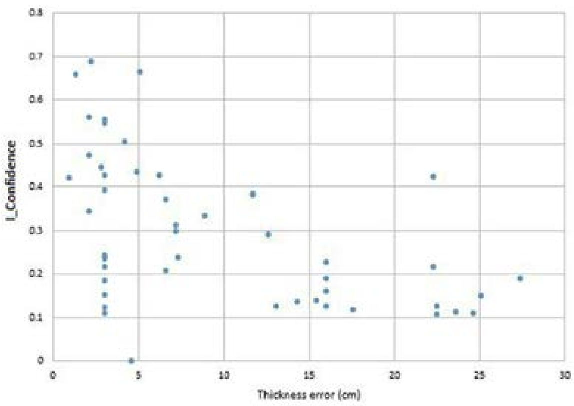
(g) $I_{coverage.}$=.23, $\varepsilon_{thickness}$ = 2.0 cm

Figure 7: $I_{coverage}$ and thickness error of sample walls

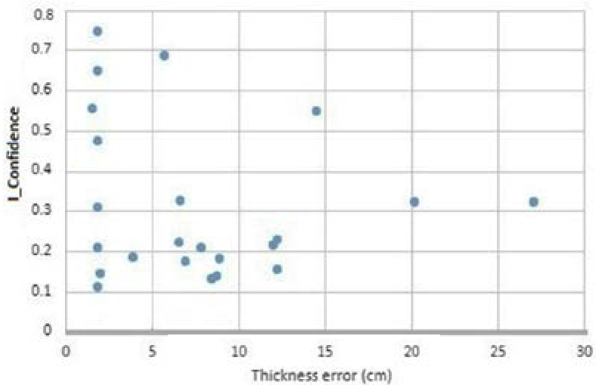
Overall, higher $I_{coverage}$, and to a lesser extent $I_{distance}$, show some level of correlation with smaller thickness modelling errors. However, in the presence of occlusion and obstruction from items such as cabinets, wall decorations, or curtains, $I_{coverage}$ is less reliable as a determinant factor for confidence of the automated Scan-to-BIM tool. To has achieve a higher correlation with the confidence of modelling, we can first look at combining these indices as:

$$I_{confidence} = I_{coverage} * I_{distance} \tag{3}$$

The results for $I_{confidence}$ are shown in Figure 8. This shows that $I_{confidence}$ has a slightly improved correlation with the confidence level of modelling.



(a)



(b)

Figure 8: $I_{confidence}$ against the thickness errors for two datasets of Spanish (a) and Greek (b).

A second observation is that, since many of the modelling thickness errors arise from the presence of pieces of furniture or decoration in close proximity to the walls as well as the confusion of the algorithm between walls and columns, it is suggested, for future work to explore the use of some point cloud semantic segmentation algorithm (e.g. (Armeni et al., 2016)), which could provide further support during the modelling as well as to refine the confidence index by ensuring that wall elements are indeed modelled with points that are mostly labelled as being in the “wall” category.

4 CONCLUSION

Users of Scan-to-BIM algorithms and generally digital twins should be provided with reliable metrics of confidence for geometric modelling; hence they do not need to check everything manually to ease quality control and corrective works.

For this purpose, we introduce indices related to coverage and distance. These indices use information to analyse estimate confidence of the modelling tool. Coverage and distance information of the point cloud and IFC models are used to determine the consistency of the modelling. The major indicator is defined based on the coverage. Information of coverage provides local qualification of the modelling. The coverage index shows the best results, but, However due to obstruction, and the presence of furniture and decorative items in close proximity of or onto walls, only fairly high values of this index (>0.8) can be used to have high confidence in modelling. The distance index can be combined with to it and to improve its results, but still further work is necessary to improve the reliability of these indices. Semantic segmentation could be employed to detect different elements such as desk, mirror, frame, cupboard, as well as distinguish columns from walls, which would then be removed before modelling and/or accounted for in the calculation of a confidence index.

ACKNOWLEDGMENTS

This work was conducted as part of the BIMERR and COGITO projects that received funding from the European Commission's Horizon 2020 research and innovation programme under grant agreements No 820621 and 958310 respectively. For the purpose of open access, the author has applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising from this submission.

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CONSTRUCTION OF A PRACTICAL FINITE ELEMENT MODEL FROM POINT CLOUD DATA FOR AN EXISTING STEEL TRUSS BRIDGE

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ABSTRACT: *The objective of this paper is to develop a semi-automatic method for constructing a practical finite element model from point cloud data of an entire span of a through-type steel truss bridge. In the first step, we introduced practical finite element models for truss bridges based on structural experiments and numerical analyses of a sway bracing located at the end support. We also proposed a basic method for semi-automatically constructing a finite element model of a sway bracing using point cloud data. This method was then extended for an entire of steel truss bridge. The point cloud data is converted to individual data structures which, in turn, are connected to construct a whole structure. The main members, such as upper chords, lower chords, and diagonals, are converted to fiber-based models by automatically creating central axis lines and cross-sections from the point cloud. The slab is converted to shell models by obtaining surfaces and thickness from the point cloud. The effectiveness of the proposed method was confirmed by comparing the analysis results from the finite element model manually created from the design drawing (drawing-model) with those obtained from the model generated by this method (point-cloud-model). The proposed method is more efficient than reading drawings and creating the models manually, and it was confirmed that the point-cloud-model shows response values close to those of the drawing-model within the design load. However, the reproducibility of the response values with more than the design load remains an issue, which can be solved by tuning plate thickness.*

KEYWORDS: *Point Cloud, Fiber-based model, Steel Truss Bridge, Structural Analysis Model, Semi-Automatic Method*

1. INTRODUCTION

A vast number of existing bridges are rapidly aging. Since it is not practical to rebuild all of them at the same time, strategic renewal through life cycle extension is required. To extend the life cycle of bridges, quantitative evaluation of the residual load capacity is being promoted through numerical analysis. The accuracy of the analytical model, such as finite element model configuration (dimensions, materials, and boundary conditions) has been verified through structural experiments and is now being realized with high reproducibility (Magoshi et al. 2014), but the efficiency of the generation method still remains an issue.

Construction of a finite element model requires acquisition of member dimensions of a target structure. However, in cases of old bridges, as-build drawings are often unavailable. In addition, conditions of bridges inevitably changed since its construction due to various factors. Therefore, it is necessary to construct a finite element model based on dimensions data instead of relying on drawings, but manual measurement is time-consuming and prone to various human errors.

Therefore, a method to efficiently construct a finite element model from point cloud data, which can efficiently reproduce the 3D shape of an object, has begun to attract attention. Some existing methods (Suzuki et al. 2019 and Nakamizo et al. 2022) convert point cloud data to a finite element model by shell or solid elements, but the shell or solid element models are not practical because of their computational burdens. In addition, such methods are only applicable to simple structures like simple beams and not to usual structures consisting of multiple members. Therefore, it is necessary to apply structures with multiple members connected to each other and to convert to fiber-based models used in practice. Fig. 1 shows a type and outline of finite element models.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Nao Hidaka, Naofumi Hashimoto, Tetsuya Nonaka, Makoto Obata, Kazuya Magoshi, Ei Watanabe, *Construction of a Practical Finite Element Model from Point Cloud Data for an Existing Steel Truss Bridge,* pp. 1147-1158, DOI 10.36253/979-12-215-0289-3.114

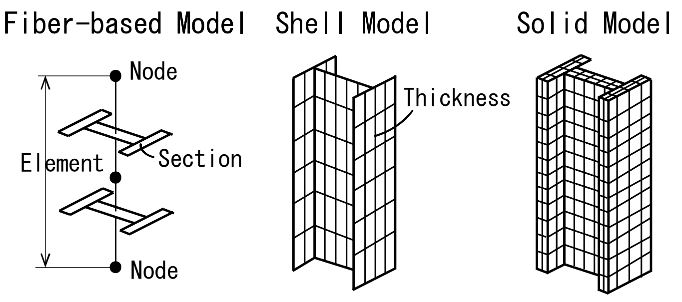


Fig. 1: The types of finite element models used in structural mechanics

The authors have developed a method for constructing a fiber-based model from point cloud data and applied a case of sway bracing located at the end support of a steel truss bridge in the structural experiment (Hidaka et al., 2023). The numerical result based on the fiber-based model constructed by the proposed method reproduced the experimental result very well. It is interesting to note that the model yields a better result than an analytical model manually constructed from the drawings. The point cloud based model can reflect accurately the state of a structure as it is. A real structure cannot avoid initial imperfections within tolerance.

In this paper, the modeling method is extended to a whole truss bridge. A semi-automatic procedure is proposed and developed to construct a finite element model from the point cloud data of the entire side span of a through-type truss bridge. To verify the validity of the model, a model created manually from drawings was also prepared, and the response values were compared under the same loading conditions.

2. CASE STUDY

A two-span continuous through-type truss bridge in Aichi Prefecture, Japan, was measured in March 2023. A photograph of the bridge is shown in Fig. 2(a). The bridge length is 136.9m with a span length of 2@67.9m. A full width is 14.3 m with sidewalks on both sides. The effective width of the roadway is 7.5 m and that of the sidewalk is 2.0 m without width widening. A slab thickness is 200 mm with a pavement of 80 mm thickness (roadway) and of 30 mm thickness (sidewalk). In addition, the bridge is straight and has a symmetric cross slope. A general bridge drawing is shown in Fig. 2(b).

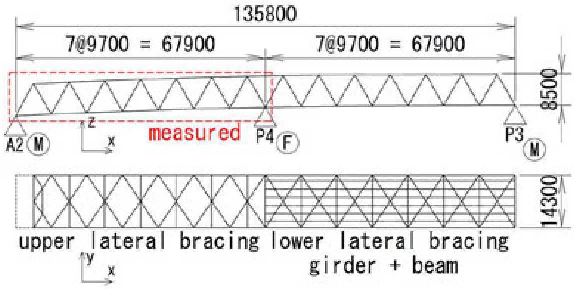
In acquisition of point cloud data of the entire P4-A2 span, the stationary laser scanner (Leica RTC360, resolution: 3mm@10m, accuracy: 1.9mm@10m) was used from the beneath of the girder and from the road surface. The number of points in the point cloud was about 1 billion. Furthermore, the handheld laser scanner (HandySCAN BLACK™ Elite, resolution: 0.05 mm@30 cm, accuracy: 0.025 mm@30 cm) was used to measure the detailed geometry of the parts of lower chords, braces, main girders, and lower lateral bracing. The lower chord, main girder, and lower lateral bracing were measured for the member closest to the abutment due to on-site restrictions, and two braces (two different cross-sectional shapes) were measured for the member closest to the pier (fixed bearing). The number of points in each point cloud was approximately 0.3 to 1.5 million. The point cloud data is shown in Fig. 2(c). The total measurement time was approximately 3 hours. The coordinate system was set so that the x-axis is along the longitudinal direction, the y-axis is transverse direction, and the z-axis is along the height direction. Table 1 shows the dimensions of each member components. Measured values, data in the as-built drawings and data by the handheld laser scanner are given.

The bridge is a two-span continuous bridge, but due to on-site restrictions, only P4-A2 span were measured; to interpolate the parameter of P3-P4 span, the altitudes of fulcrum at both ends were measured with a total station.

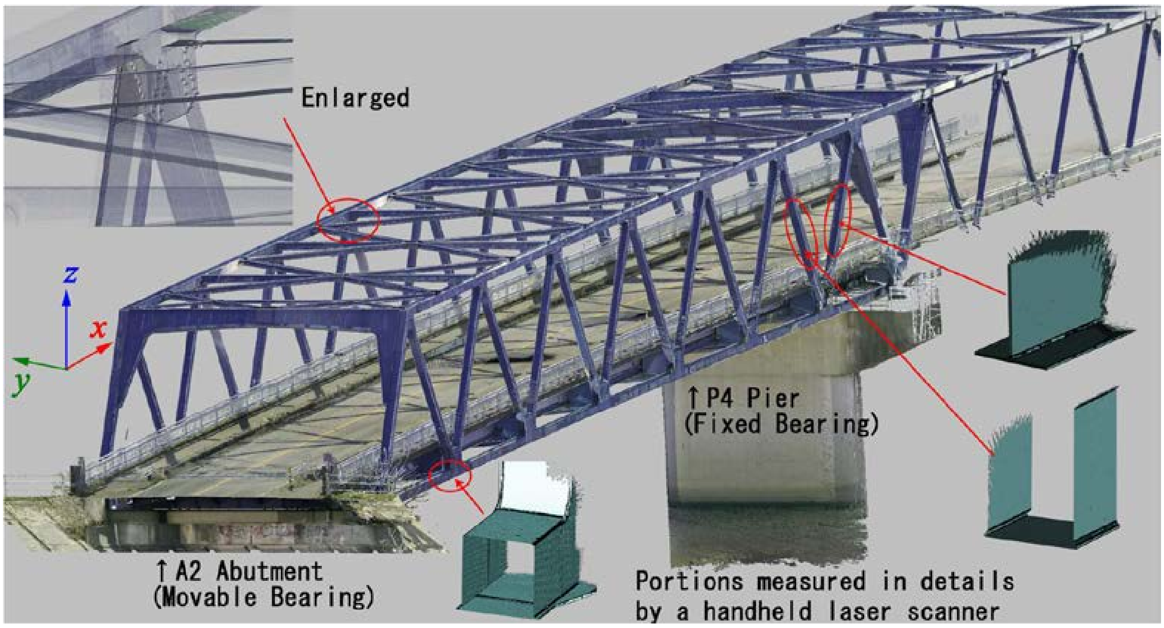
3. PROPOSED METHOD

A computer program is developed to generate fiber-based models for numerical analysis from point cloud data obtained in Chapter 2. To construct a fiber-based model, nodes along an axis passing through a center of each member, elements connecting the nodes, a cross-sectional geometry of each element, and other material and loading conditions are required.

(a) The case study bridge



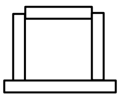
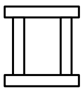
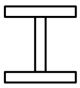
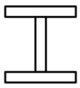
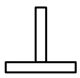
(b) General bridge diagram



(c) Measured point cloud data

Fig. 2: The case study bridge and measured point cloud data

Table 1: Arrangement of measured dimensions of bridges

			Lower chord			Brace (Compression)			Brace (Tension)			Main girder			Lower lateral bracing		
Cross section																	
			D	M	H	D	M	H	D	M	H	D	M	H	D	M	H
Length	Flg.	U	380	379.1	380.8	350	351.0	351.1	350	352.0	351.2	230	230.0	230.2	360	361.0	360.9
		L	460	462.3	461.8												
	Web		380	378.0	379.1	340	339.1	340.7	322	324.0	—	1000	1002.3	—	180	180.3	180.6
Thickness	Flg.	U	9	—	8.5	19	19.4	19.3	22	22.5	22.4	14	14.2	14.2	19	19.5	19.3
		L	10	11.1	10.6												
	Web		11	11.3	10.9	19	—	—	22	—	22.3	9	—	9.4	16	17.0	16.5

(Unit: mm)

D: as-built drawings, M: manual measured, H: handheld laser scanner, U: upper, L: lower, -: not measurable

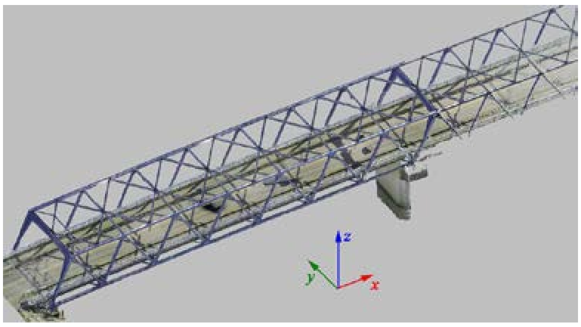
3.1 Creating nodes and elements for a fiber-based model from a point cloud

In the first step, nodes and elements are created from point cloud data. In this step, taking advantage of the fact that braces of the truss bridge are connected to many members (such as upper and lower chords, upper and lower lateral bracings, and cross beams), nodes, the central axes of the braces are extracted from the point cloud data of the entire bridge, and the nodes and elements of the fiber-based model are created by making the points of intersection between the central axes of adjacent braces as grid points.

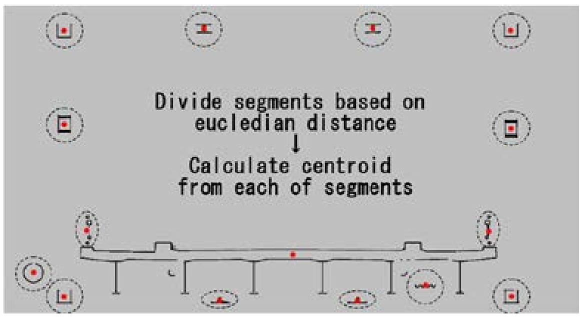
First, point cloud data of the entire bridge (Fig. 3(a)) is sliced along a longitudinal direction (in this case, the x-axis direction) from an abutment position at small intervals. A cross-sectional point cloud is obtained as shown in Fig. 3(b). By grouping points in the cross-sectional point cloud based on the Euclidean distance (Ester et al., 1996), point groups of cross sections of each member (such as upper and lower chords) are separated. Centroids of these cross sections correspond to a center axis of each member, and if continuing to slice, candidate points for the center axis of the members are created as shown in Fig. 3(c). If location of centroid is obtained by a simple average method, it is biased by the density of point cloud data. To avoid the bias, cross-sectional point cloud is converted to polyline with the convex hull (Preparata and Hong, 1977) method and a centroid is obtained using an image processing algorithm.

Next, central axes are obtained from the candidate points for the center axis using the RANSAC method (Fischler and Robert, 1981). In the above procedure, however, central axes of other members than braces are inevitably included. The central axes of braces can be extracted by using a threshold value method based on the fact that they extend in the x- and z- directions. To create intersections of the central axes of the adjacent braces, the central axes are sorted as x-coordinates of the center points in the axes. When the two lines are in a twisted position, the intersection is defined here as a midpoint of a line segment that is orthogonal to two lines and has the shortest length. After creating the grid points, nodes are sampled at equally spaced intervals along the line segment connecting the two grid points, with the specified number of nodes. For the upper lateral bracing, its grid points are located at the center of the upper chords.

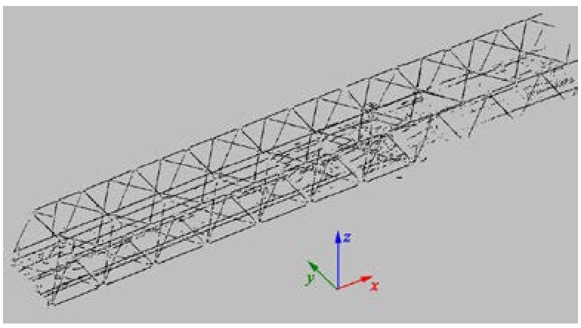
Since grid points, nodes, and elements of main girders cannot be created from grid point of braces, they are created additionally. Fig.4 shows a summary to create grid points of main girders. A cross-sectional point cloud perpendicular to longitudinal direction at a location of a cross beam is obtained. Points within 1 m of the upper side of a line connecting grid points of lower chords (bottom horizontal line in Fig. 4) are extracted and divided point groups of main girders and others based on Euclidean distance. To extract main girder lines, the divided into point groups are converted into direction vectors by using principal component analysis and only the z- direction vectors are extracted as main girder lines (blue vertical lines in Fig. 4). Intersections of main girder lines and a line connecting grid points of lower chords are grid points of the main girders. To account for the possibility that grid points cannot be created at a few of cross beam positions, the average value of the created grid points was calculated. After creating grid points, if there is a cross beam position where the grid points cannot be generated by the above procedure, the calculated average value is applied.



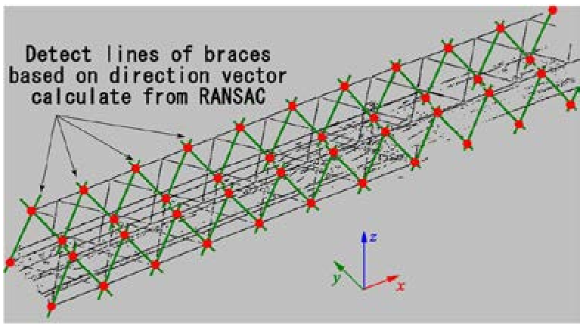
(a) Input point cloud



(b) Cross-sectional point cloud along longitudinal direction



(c) Centoroids obtained from cross-sectional point clouds



(d) Detected lines of braces and grid points

Fig. 3: Creating grid points of braces by using cross-sections and centroids

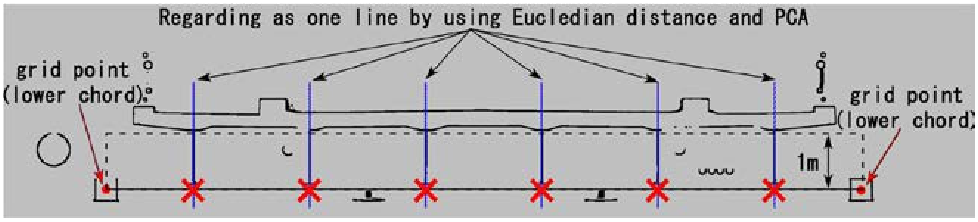


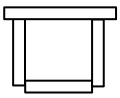
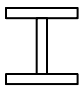
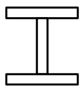
Fig. 4: Creating grid points of main girders (cross mark is a grid point)

3.2 Obtaining a cross-sectional geometry of each member for a fiber-based model from a point cloud

In the second step, once the nodes and the elements have been created, the next step is to obtain a cross-sectional geometry to be applied to the elements. In finite element models, a cross-sectional geometry is represented by a collection of rectangles as shown in Fig. 5. The rectangle is defined by the coordinates of a start and an end point and its thickness. The coordinate system of the cross section must be converted to a two-dimensional coordinate system (such as u-v coordinate system) with the origin at the position through which the element axis lines pass.

Cross-sectional geometry is obtained using cross-sectional point cloud perpendicular to a direction vector of the element passing through the midpoint of the element. Because point cloud measured by the stationary laser scanner (accuracy: 1.9mm@10m) is difficult to ensure accuracy of plate thickness, representative cross-sectional geometry is obtained from the point cloud data measured by the handheld laser scanner (accuracy: 0.025 mm@30 cm), and is applied to all the elements of the corresponding member. In addition, for the upper chords, the upper lateral bracing, and the cross beams which could not be measured by the handheld scanner due to on-site restrictions, the vertical and horizontal scales of cross sections of other members with similar shapes were adjusted. Specifically, the cross-sectional geometry of the upper chords is a vertically inverted that of the lower chords, the upper lateral bracing applies the I-section of the braces, and the cross beam applies to the cross-sectional geometry of the main girder. Table 2 shows the relation of them. For members whose entire surface could not be measure by the handheld laser scanner due to on-site restrictions, the symmetric center point of the cross-section at the same position was obtained from the point cloud data collected by a stationary laser scanner. Subsequently, the cross-sectional geometry was determined by duplicating the measured portion through rotational symmetry, utilizing the point symmetry of the cross section. In the following, the methods of obtaining cross-sectional geometry are explained according to the type of geometry.

Table 2: The relation of applying cross-sectional geometry of members that could not be measured by the handheld laser scanner

Unscanned member	Upper chord	Upper lateral bracing	Cross beam
Referenced member	Lower chord	Brace (Tension)	Main girder
Cross section			

3.2.1 Open cross-section (I-shape and T-shape)

Midpoints of all point pairs in a cross-sectional point cloud are created (Fig. 6(a)), and the midpoints that are not on the cross-sectional point cloud are extracted as points of candidate centerlines. These are converted to straight lines by using RANSAC (Fig. 6(b)), intersection points of these lines and the cross-sectional point cloud are starting and ending points (Fig. 6(d)), and its thickness is obtained by doubling an average of the shortest distances from the cross-sectional point cloud (Fig. 6(c)).

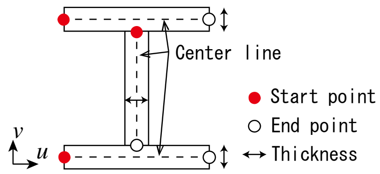
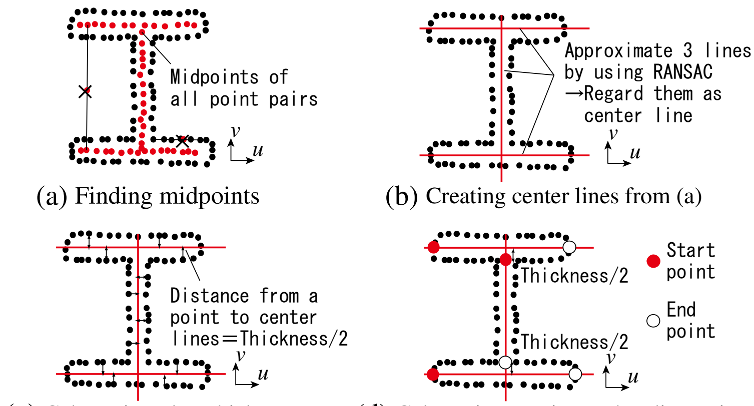


Fig. 5: Parameters of section for fiber-based model



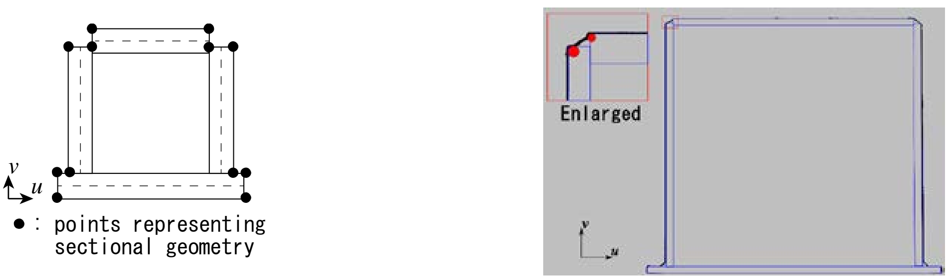
(a) Finding midpoints (b) Creating center lines from (a)

(c) Calcurating plate thickness (d) Calcurating starting and ending point

Fig.6: Obtaining parameters of open-cross section

3.2.2 Close cross-section (quadrangle-shape)

The algorithm in 3.2.1 cannot be applied to a square cross section because back sides of plates cannot be measured. Therefore, as shown in Fig. 7(a), cross-sectional geometry is constructed by finding points at corners. Since corner points and joint positions are rounded, as shown in Fig. 7(b), corner points can be found by taking a local area at all points of the cross section and extracting the area where the radius of the circle is smaller when fitting it to a circle. For areas where thickness cannot be measured, such as the web and the upper flange of the lower chord, general plate thicknesses are used.



(a) Cross-sectional geometry of quadrangle-shape (b) Finding corner points by fitting to circles

Fig.7: Getting parameters of close-cross section

3.3 Creating a slab model as a shell model

Only in a case of modeling for a slab, to reproduce load sharing of live load accurately, a shell model is constructed. It is connected to main girders and cross beams in the fiber-based model with springs. As shown in Fig. 8, a position of a slab is determined by finding the difference in z-coordinates between the main girder grid points and a centerline of the slab, and offsetting the z-coordinates from the main girder grid points by that value. In the same way as in Sec. 3.2.1, a centerline of a slab is obtained by finding midpoints of all point pairs in a cross-sectional point cloud of a slab and extracting points of a candidate centerline that are not on the cross-sectional point cloud. This is converted to a straight line, and the average of the shortest distances from the cross-sectional point cloud of the slab is doubled to obtain the slab thickness. As the slab thickness obtained in the above procedure includes the pavement portion, the thickness after substracting a typical pavement thickness of 80mm is used.

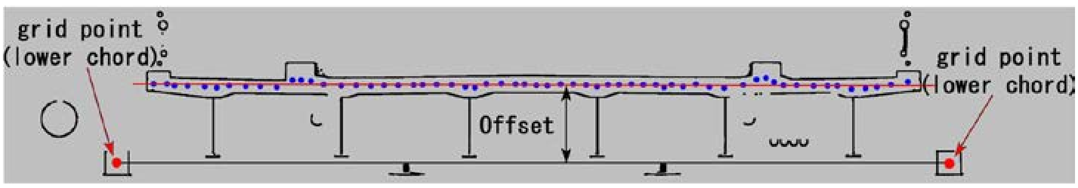


Fig. 8: Obtaining offset and thickness parameter of a slab

3.4 Implementation

The proposed methods were applied to the point cloud data in Chapter 2. Due to memory limitations, the point cloud data measured by the stationary laser scanner was down-sampled from approximately 1 billion points to approximately 200 million points (3 mm pitch). Only the nodes and elements in P4-A2 span were created from the point cloud data, and those in P3-P4 span were extrapolated by duplicating the linearly stored height of the grid using the altitudes of fulcrum difference. Table 3 shows the development environment.

The program that implements the proposed method is divided into several phases because it requires several manual operations in the process. The program flow is shown in Fig. 9.

Table 3: Development Environment

CPU	Intel(R) Xeon(R) Silver 4214R CPU @ 2.40GHz 2.39 GHz (2 processors)
Memory	64GB
GPU	NVIDIA GeForce RTX 3080 (10GB)
OS	Windows 10 Enterprise 22H2 64bit
Development Environment	Microsoft Visual Studio Community 2022 64bit
Library	Point Cloud Library (PCL) 1.12.0 64bit (Rusu, 2011), OpenCV 4.5.5 64bit
Programming Language	C++
Structural analysis software	SeanFEM (Earthquake Engineering Research Center Inc., 2007)

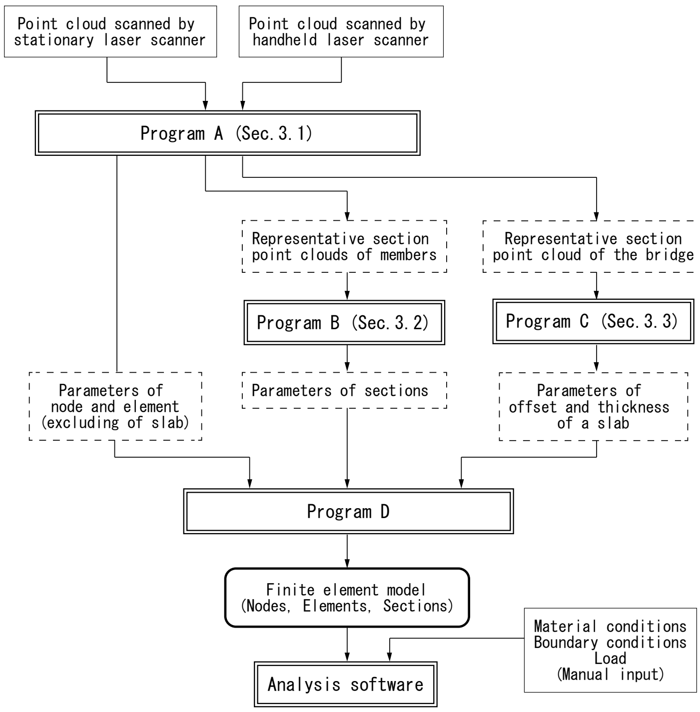


Fig. 9: The flow of implement for the proposed method

First, the nodes and the elements excluding for slab are obtained by inputting the point cloud measured by the stationary laser scanner and the handheld laser scanner into Program A, which performs the procedure described in Sec. 3.1. To obtain the cross-sectional geometries, the representative cross-sectional point cloud of each member is output. Furthermore, to obtain the nodes and the elements of the slab, the representative cross-sectional point cloud of the bridge perpendicular to longitudinal direction is output.

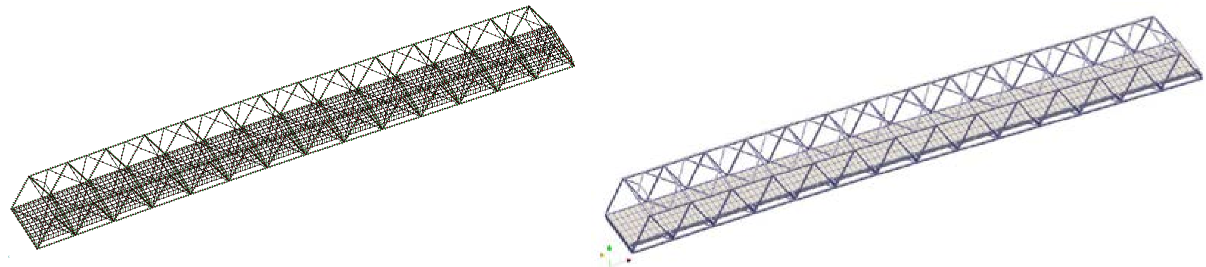
Next, in order to obtain the cross-sectional geometry, the missing part is manually compensated, and the scale is adjusted to apply to other members. After that, they are input to Program B, which performs the processing described in Sec. 3.2.

After the slab points are manually extracted from the cross-sectional point cloud data, they are input into Program C that performs the procedure described in Sec. 3.3.

Finally, the output results of Programs A, B, and C are input to Program D, which outputs the finite element model. Once the nodes, elements and cross-sections are obtained in this way, the material and boundary conditions are manually specified and entered into the analysis software.

Excluding manual operations such as preliminary down-sampling and correction of missing points in the cross-sectional point cloud, it took 35 minutes to input the stationary laser scanner point cloud, create the KD search tree, slice the cross-section in the 100 mm pitch in the longitudinal direction, divide them using the Euclidean distance, and obtain the centroid of each member cross-section. In addition, it took 1 minute to extract the central axis of the braces from the point cloud of the centroid, 6.5 minutes to obtain the grid point position of the main girder, and 1 minute per section to obtain the end point and plate thickness of the cross section. The remaining processing was completed in less than 1 second.

The generated finite element model is shown in Figs. 10. (a) is the framework element, and (b) is the cross-sectional geometries reflected on it.



(a) Framework element (b) Cross-sectional geometries reflected on

Fig. 10: The analysis model from point cloud by using the proposed method

4. RESULTS AND DISCUSSION

4.1 Results of repeatability analysis

The response values of nonlinear analysis were analyzed by applying progressively increasing dead and live load according to the Japanese Specification for Highway Bridges (Japan Road Association, 2017). Dead load is loaded to whole of the bridge and live load is loaded as Fig. 11. The material conditions and reinforcement of the slab were set based on actual bridge design experience. To verify the validity of the model, the same loading conditions were applied to a model created manually from drawings. Hereafter, the finite element model generated by the proposed method will be referred to as the "point-cloud-model" and the model from the drawing as the "drawing-model".

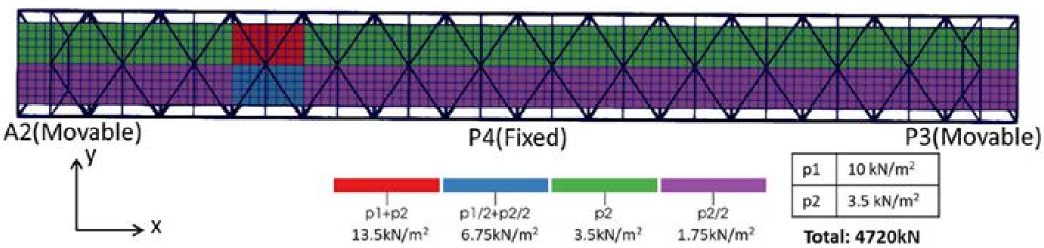


Fig. 11: Live load

The displacement of the point-cloud-model was close to that of the drawing-model within the design load that is the sum of dead and live load. Additionally, when examining the strain contour and deformation diagrams for the design load (Fig. 12), the deflection of the bridge exhibited a nearly identical behavior between the two models. However, with a load larger than the design load, the response value of point-cloud-model was different to the drawing-model (Fig. 13(a)). As the deformation diagram of the point-cloud-model for the 1.3 times of the design load (Fig. 13(b)), one upper chord at left-side in the center span of P4-A2 was extremely deflected. Consequently, a discernible variance arose between the response of the point-cloud model and that of the drawing model.

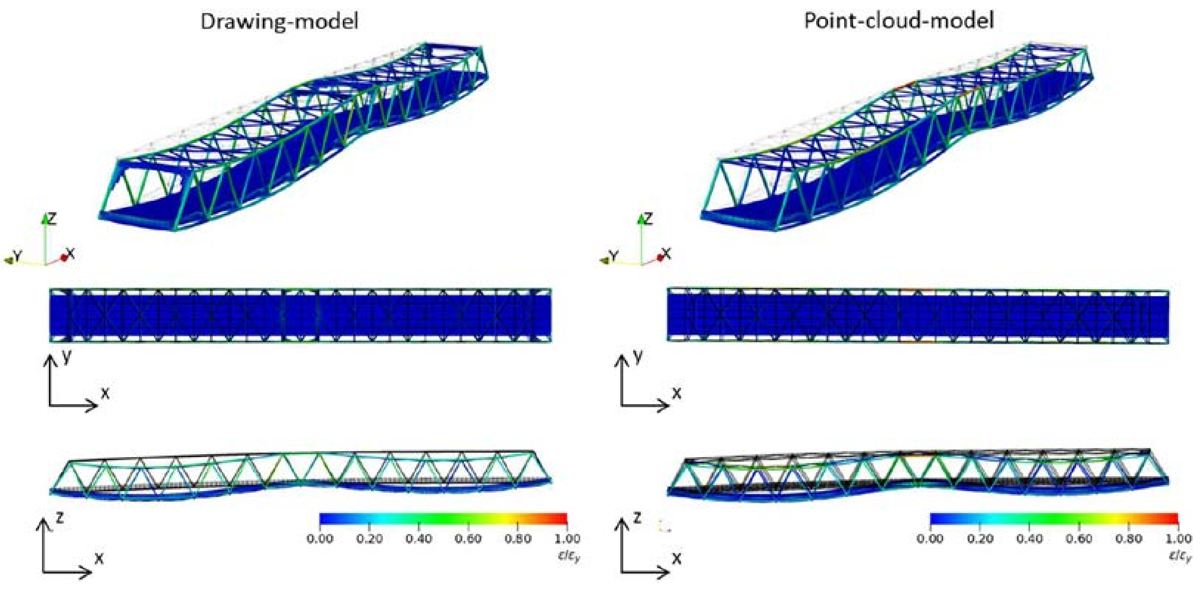
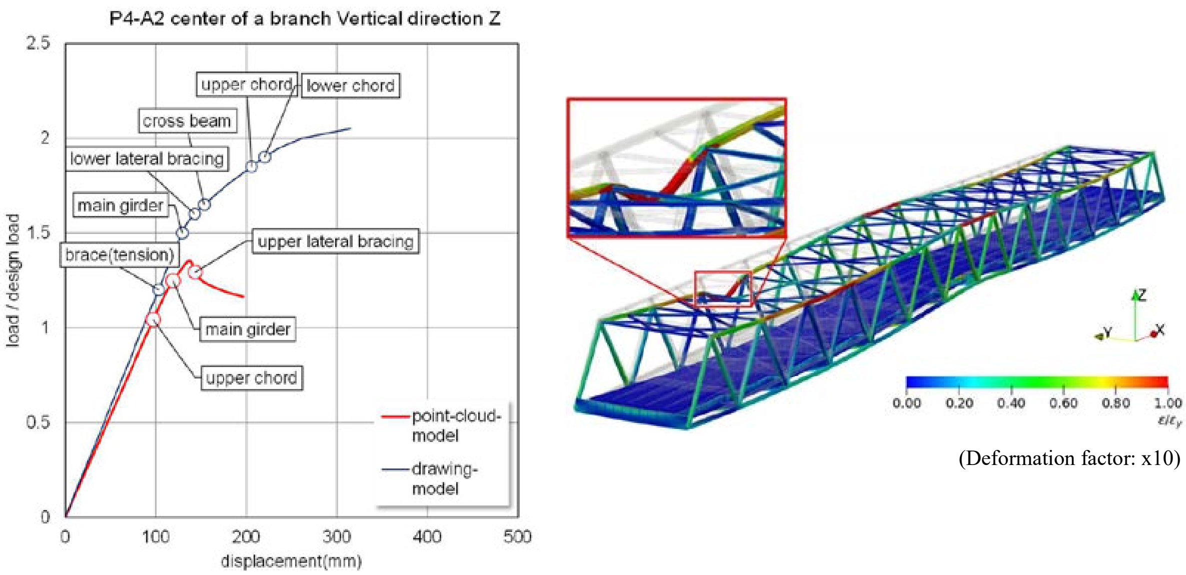


Fig. 12: Strain contour and deformation for the design load



(a) Load-displacement curve (open circles represent the yield points of individual members)

(b) Strain contour and deformation

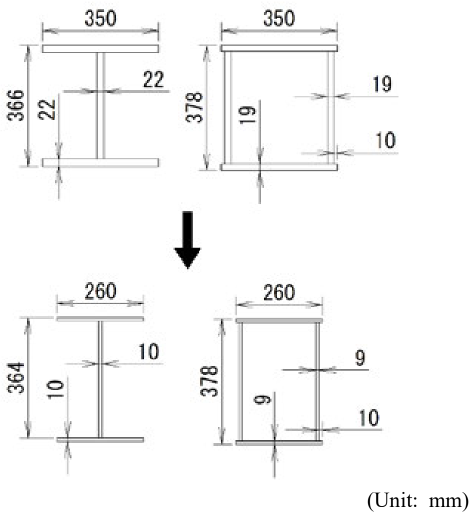
Fig. 13: Response value for the 1.3 times of the design load

4.2 Discussion

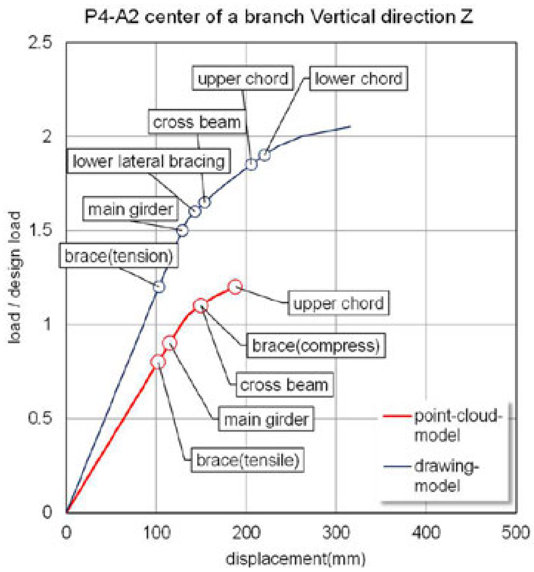
To improve maintenance efficiency, a method was developed to semi-automatically construct a fiber-based model (the slab is a shell model) that reproduces the structure of a truss bridge from point cloud data. When the drawing-model was created manually from drawings, it took several days to read the dimensions and connections of the members and input them into the software. In particular, the most time-consuming step was the input of cross-sectional geometries due to variations in plate thickness. The point-cloud-model, on the other hand, took about three hours to measure the point cloud data and less than one hour to generate the model from the point cloud data. Other manual work, such as processing noise and filling missing portions in the cross-sectional point cloud, can still be completed in 12 to 24 hours. The proposed method is expected to contribute to efficient maintenance and management.

However, there are several issues related to the accuracy of elemental axis construction and the limits to applicable structures.

The point-cloud-model demonstrated a response closely aligned with the drawing-model under the design load. However, deviations emerged with a load larger than the design load. One plausible explanation stems from the inherent variability in plate thicknesses and member dimensions among upper chords, lower chords, braces, and lower lateral bracings unlike the brace panel in the previous research (Hidaka et al., 2023). The point-cloud-model encompasses disparities in cross-sectional geometries, as the stationary laser scanner's limited measurement precision and the handheld laser scanner's constrained range preclude the complete capture of all such geometries. Notably, the upper chord's cross-sectional geometry, pivotal for truss bridges experiencing significant forces, eludes handheld scanner measurement and significantly influences analytical outcomes, as evident in Fig. 13(b). Furthermore, the substitution of a representative, thinner cross-sectional geometry for the braces at the span's center, as described in Fig. 14(a), led to a marked reduction in overall bridge stiffness (Fig. 14(b)). These findings underscore the notion that a uniform approach to determining cross-sectional geometries across members with varying plate thicknesses sacrifices precision. Thus, an enhanced methodology is imperative to refine cross-sectional geometries and achieve heightened accuracy.



(a) Cross-sectional geometry



(b) Load-displacement curve (open circles represent the yield points of individual members)

Fig. 14: The case of braces with thinner cross-sectional geometry

In the previous research (Hidaka et al., 2023), the fiber-based modeling approach was employed for simulating sway bracing. This involved adjusting node positions to accurately replicate member bending by utilizing centroids within localized regions. The incorporation of this technique successfully accounted for initial irregularities, resulting in a response that closely aligned with the actual structural behavior. However, in the present case, this method couldn't be employed due to its limited accuracy in centroid generation. This limitation stemmed from numerous factors, including the presence of numerous gaps in the point cloud data as well as the inclusion of extraneous points within local regions intended for centroid calculation. As such, there exists a pressing need to enhance the methodology in order to effectively surmount the aforementioned challenges. The proposed method is based on an algorithm that uses advantage of the fact that the bridge is a straight and has no widening and same truss spanning. It is required to improve the method to extend to curved or width extension bridges. A longitudinal direction of curved bridges and width widening may be obtained by tracing line of curb stones and white lines, for example. In addition, it may be effective to supple missing geometries and dimensions by using information of similar bridges.

5. CONCLUSIONS AND FUTURE WORK

In this paper, a method is proposed to semi-automatically generate a finite element model for practical use from a point cloud data for the entire of steel truss bridge without using drawings. The findings are as follows:

- The method to accurately obtain the geometry and member dimensions of the entire bridge was proposed by using stationary and handheld laser scanners.

- A program to construct a finite element model from a point cloud data was developed and its usefulness was demonstrated.
- The proposed method showed the response value is close to the drawing model within the design load, but it is required to improve detailed analysis results with more than the design load. A possible reason for this is that the representative section was uniformly determined for members although they have non-uniform thickness.

In the future, we will address the issues of dealing with various plate thickness and curved bridges, and interpolation of unmeasured points using other dimension data and other parameters, such as road alignment. In particular, for applying appropriate cross-sectional geometries, the following two proposals are seen to be effective and will be implemented.

- A method to determine appropriate members for measurement by using a handheld scanner will be developed. It is useful to estimate the members that are subjected to large cross-sectional forces according to the structural characteristics of a bridge type and span. Additionally, numerical analysis enables us to determine the members whose cross-sectional dimensions require high accuracy, such as the upper chords and diagonals in this particular project.
- We are in the process of devising a methodology to extrapolate cross-sectional geometries from point cloud data measured by a stationary laser scanner. Despite the inherent precision limitation to a few millimeters associated with the stationary laser scanner's point cloud, it facilitates the extraction of crucial details concerning member classification, cross-sectional profiles, and member lengths. Leveraging this data, an effective approach to determine the suitable plate thickness can be formulated.

6. ACKNOWLEDGMENT

This research was supported by JSPS Grant-in-Aid for Scientific Research JP22K20445, Nao Hidaka.

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A BIM-BASED FRAMEWORK FOR FACILITY MANAGEMENT DATA INTEGRATION IN HERITAGE ASSETS

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ABSTRACT: *The operational phase of a real estate asset accounts for approximately 80% of the overall investment and management costs throughout the entire life cycle of the building, and the activities of space management and monitoring of building components and systems play a crucial role in ensuring the well-being and health of users. The AECO (Architecture, Engineering, Construction, and Operation) industry is transitioning towards a new framework governed by data-driven processes. In this context, Building Information Modeling (BIM) can support the utilization of big data generated throughout different stages of the building's life cycle, thereby establishing itself as a dynamic repository of information at the center of a constellation of systems used by a Facility Management body to achieve specific objectives (such as CAFM, ERP, BMS, etc.).*

The proposed study aims to define a processing framework for the collection and management of data aimed at the implementation of DT of existing real estate assets, created based on the integration between BIM platforms and IoT technology oriented to subsequent developments of big data analytics and AI applications. The objective is to support in the operational phase of buildings the decisions of the various operators involved in planning scheduled and/or corrective maintenance actions and to generate content, recommendations, best practices by formulating predictive analysis on managed assets. In particular, a critical analysis is made of the various approaches available for the definition of an IT architecture to support IoT reference models, which will find application in the monitoring of some existing assets of the University of Florence's real estate managed by the Building Area, digitally implemented on a BIM platform. The contribution is part of a broader research activity carried out as part of the PNR Project, "BIM2DT. BIM-to-Digital Twin: information management to support decision-making in the building life cycle."

KEYWORDS: *Facility Management; HBIM; Digital Twin, IoT.*

1. INTRODUCTION

For several years now, the digitization of the construction process has been a primary objective of governments, organizations and in general stakeholders in the AECO sector (Daniotti et al., 2022) to reconfigure a production sector that, with different graduations in different countries around the world, lags historically behind the manufacturing sector in gathering the benefits that technological and process innovation through Information Technology can return in terms of efficiency, competitiveness and economic, environmental and social sustainability.

In particular, the introduction of regulations at the national and international level regarding the information management of the construction process with Building Information Modeling (BIM) tools and methodologies in public supply, service, and works contracts has necessitated the redefinition of structured and planned flows of data and information exchange between the various stages of the delivery and operation process of real estate assets. More recently and in line with the Industry 4.0 approach, many organizations and business operators are orienting their decision-making processes toward data-driven strategies especially in the management of complex estate assets (Mêda et al., 2021). In fact, the operation phase engages about 80 percent of the total investment and management costs of a building's life cycle (Volk et al., 2014), and the management and monitoring activities of spaces, building components, and facilities play a decisive role in ensuring the well-being of users and health and safety in living and working places. The use of BIM in Facility Management for an organization therefore becomes a key step in improving and optimizing the operation and maintenance activities of managed assets and, in a broader perspective, in contributing significantly to achieving the goals set by the European Green Deal and Sustainable Development Agenda 2030 (Ciribini et al., 2016; Mirarchi et al., 2018).

Currently, information management of an existing asset in the operation phase is conducted through different tools and platforms, including Computerized Maintenance Management System (CMMS), Computer-Aided Facility

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Carlo Biagini, Alberto Aglietti, Luca Marzi, Andrea Bongini, *A BIM-Based Framework for Facility Management Data Integration in Heritage Assets,* pp. 1159-1170, DOI 10.36253/979-12-215-0289-3.115

Management (CAFM), Building Automation System (BAS), Integrated Workplace Management System (IWMS). However, there is a lack on creating an integrated system to manage multiple information distributed on different databases. In this context, BIM can act as a centralized repository that can hold all the information about the building and its surroundings (Qiuchen Lu et al., 2019). In fact, much of the information produced in the design and construction phases is lost and only a small portion is passed on to the next operation phase usually in the form of spreadsheets with 3D information added according to client specifications. This loss of information can be avoided, or at least reduced, through the use of standardized and shared practices and procedures among the different actors in the supply chain, but also through open and interoperable exchange formats (Patacas et al., 2015). This type of information, which we can define as "static", can also be combined with "dynamic" information from the collection of heterogeneous data, both in terms of protocols and formats, during the use and management phase of the real estate.

In particular, the rapid spread of the Internet of Thing (IoT) in daily activities has made available real-time data and information on many aspects of the operating conditions of buildings and their surroundings, which can be usefully employed by facility managers to improve building performance management, reduce energy consumption, optimize routine and extraordinary maintenance operations and increase user satisfaction and well-being. All this leads to the creation of a "digital twin" (Boje et al., 2020) of the building aimed at the management of existing assets, enabling a two-way exchange of information between the physical and digital worlds.

This contribution represents a first outcome of a wider research activity within the PNR Project, *"BIM2DT. BIM-to-Digital Twin: information management to support decision-making processes in the life cycle of buildings"*, which intends to define an operational framework for the collection and management of data aimed at the implementation of DTs of existing real estate assets, created on the basis of the integration between BIM platforms and IoT technology oriented to subsequent developments of big data analytics and AI applications. The objective is to support the decisions of the various operators involved in the planning of scheduled and/or corrective maintenance actions in the operational phase of buildings, and to generate content, recommendations, and best practices by formulating predictive analyses on managed assets. In particular, it is proposed a critical analysis of the various approaches available for the definition of an IT architecture that supports an IoT reference model, which is structured according to protocols parallel to those that today support the Internet infrastructure. The IoT model thus identified, will find application in some existing assets of the University of Florence's real estate managed by the Building Area, digitally implemented on a BIM platform.

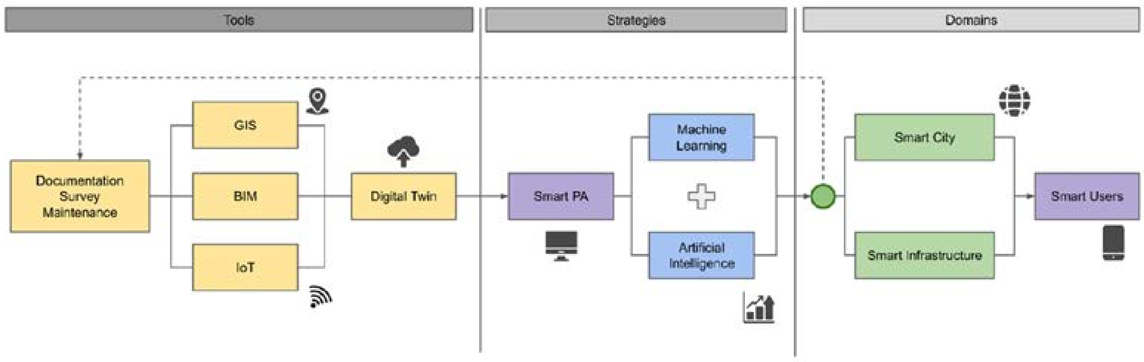

Fig. 1 – Conceptual outline of the BIM2DT research project theme

2. INTERNET OF THINGS FOR THE MANAGEMENT OF BUILT ASSETS

Buildings are complex systems, from which a large amount of data (environmental, comfort, security, ...) can be collected by Building Management Systems (BMS). This data, which until now was stored locally, is moving to a cloud environment, increasing the adoption of IoT solutions. The BIM methodology itself is evolving with web-based and data-driven solutions. A major problem is the heavy reliance on native solutions that confine facility managers to proprietary platforms and do not provide the opportunity to develop evaluations across multiple systems. The information associated with BIM elements is also usually unusable outside modelling environments, and only a few applications have started to integrate data from different types of sensors. With the increasing demand for smart buildings, there is therefore a need to develop applications capable of accommodating heterogeneous data, which are transmitted according to different formats, protocols and languages. The starting point, however, must be an understanding of the infrastructure that revolves around the world of the Internet of

Things and how this can be used to improve and implement the semantic content of information models produced using BIM methodology.

2.1 Internet of Things Model

The term Internet of Things (IoT) was first coined in 1999 by British engineer Kevin Ashton, co-founder of the Auto-ID Center at MIT (Ashton, 1999). In 2001, the MIT Auto-ID Center presented its vision on the topic of IoT, which the International Telecommunication Union (ITU) later drew on in its 2005 Internet Report. The latter defines the term IoT as *"a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies"* (Overview of the Internet of Things, 2012). The Internet Society instead speaks of IoT technologies as *"scenarios where network connectivity and computing capability extends to objects, sensors and everyday items not normally considered computers, allowing these devices to generate, exchange and consume data with minimal human intervention"*. Beyond the definitions, of which there is still no universal one (Rose et al., 2015), we can conclude that around the topic of IoT, new scenarios are developing concerning the tools and methods of digital management of building assets.

When we speak of the Internet of Things, we are referring to any type of smart object capable of connecting to the Internet via a wired or wireless connection (through a dual communication capacity: M2M, machine-to-machine, and M2H, machine-to-human), and consequently having an active role within the communication processes. In order to be able to define a smart object, however, we need certain fundamental characteristics: the sensing component, i.e., the ability to gather information from the real world or to perform an action following an input, a unique identifier to identify the source from which the data is received, a connection to the Internet, for communication and notification of the information, and finally, one or more software platforms for the analysis and processing of the data collected

The term IoT, in its simplest form, can thus be considered as the intersection between the internet infrastructure, objects and data. Other more complex definitions, however, lead to the inclusion of standards and processes, as these technologies make it possible to connect objects to the internet in order to exchange data according to industry standards that guarantee interoperability and enable the execution of mostly automated processes. We thus find ourselves having to manage not only an exchange of information between individuals but also between single devices. The potential applications of this technology are many, from smart home to smart cities, smart healthcare, smart retail or even connected cars.

The main question to be asked is therefore how it is possible to achieve this type of interaction between very often heterogeneous systems and tools and to provide a simple and immediate service for the end user, both in the working environment and in everyday life actions. To address these problems, communication standards were created for specific areas, corresponding to the heterogeneous application areas of the IoT. We may, for example, have the need to have efficient communication with minimum packet loss but at the same time have a latency that allows communication to be defined almost in real time, or we may have the need for a less reliable protocol but with the peculiarity of operating on low performance and low power hardware. Each protocol offers certain functionalities or combinations of functionalities that make it preferable to others. Recurring factors that determine the preference of one protocol over another include geographical location, power consumption, physical barriers and hardware cost.

The inapplicability of classical communication protocols even in the context of IoT devices depends on the minimal requirements in terms of hardware and power consumption required by these devices. It has therefore become necessary to develop new technologies that do not require complex computational efforts for sometimes very simple devices. The fundamental objective of an IoT architecture is to connect the physical world with the digital one, and over the years many entities, both international organizations and individual developers, have implemented new communication mechanisms, leading us today to have a wide choice of protocols at our disposal. Protocols that, however, were not designed to interact with each other, as they are based on different concepts and ideas. International organizations therefore, in order to prevent the vertical fragmentation of different commercial solutions, have set themselves the goal of defining open communication standards and mapping the traditional IP-based stack to the new IoT concept, understood as a network of heterogeneous devices connected to each other. Cisco, IBM and Intel have proposed an IoT reference model (fig.2) to standardize the concepts and terminology used in the IoT world based on seven levels. These levels are represented by:

1. physical devices and controllers: these are terminals that send or receive information;
2. connectivity and communication between objects and networks: information must flow both horizontally between objects within the network, and vertically between different networks; gateways may be introduced for older devices not equipped with IP;
3. edge/fog computing: is the data processing layer closest to the network with minimum latency from the data collection point;
4. data accumulation: is level of data collection and storage; converts data-in-motion to data-at-rest;
5. data abstraction: level of data aggregation from multiple devices and simplify data access to the application by creating schemas and data views;
6. applications: provide the desired output through the interpretation of available information;
7. collaboration and processes: level of involving people and business processes to make IoT application useful.

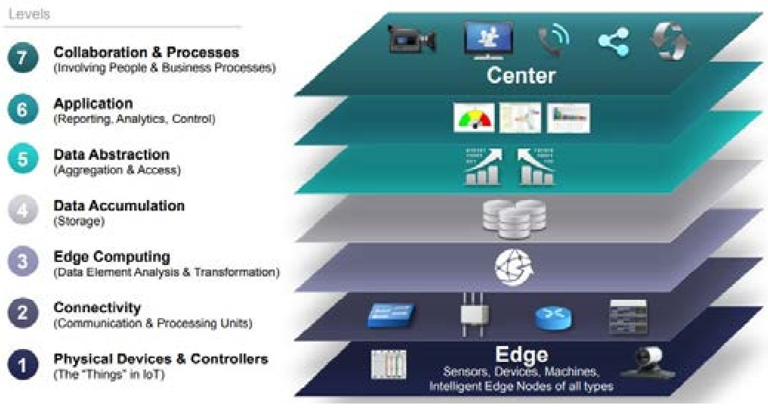

Fig. 2: IoT Reference Model presented at IoT World Forum by Cisco, IBM and Intel

This reference model follows the subdivision already used for the Internet, namely the OSI (Open Systems Interconnection) model, which consists of seven layers grouped into three media layers (physical layer, link layer and network layer) and four host layers (transport layer, session layer, presentation layer and application layer). Technologies such as Bluetooth and Wi-Fi use the lower communication layers while DDS or MQTT use, for instance, the application layer.

2.1.1 IoT Devices

The first elements that make up an IoT network are the devices themselves, which can be grouped according to their characteristics. According to the ITU, hardware platforms can be classified according to their computational and connection capabilities into three classes (Bormann et al., 2014):
a) class 0, devices very limited in memory and information processing capabilities that sometimes do not even have the necessary resources to communicate directly with the internet in a secure manner and therefore rely on other devices such as proxies, gateways or servers;
b) class 1, devices with certain limitations and that cannot talk to other nodes on the internet that use "a full stack protocol as HTTP, TLS and related security protocols and XML-based data representation". However, they are able to use a specific protocol stack for limited nodes such as COAP and participate in the conversation without the use of gateways;
c) class 2, less limited devices capable of supporting the same protocol stack as servers or notebooks. They can still benefit from the use of lighter and less energy-consuming protocols. Devices such as Arduino and Raspberry microprocessors fall into this class.

From this classification, it can be seen that not all devices are able to connect to the Internet or process the collected data in situ. To facilitate the transit of information to the end platforms and to reduce the computational load, gateways are introduced, i.e. elements used, not necessarily, to establish communication from one device to another or to connect IP-based devices, which are not able to connect directly to the cloud environment. The data collected by IoT devices is in this case transmitted to a gateway, processed in the perimeter devices and then transmitted to the cloud. The use of gateways reduces latency and transmission size and also offers a higher level of protection to data-in-motion. When data is processed locally by the same device that collects it, it is called *edge computing*; when it is sent to a gateway for peripheral processing, it is called *fog computing*; and when it is sent and processed within a cloud-based repository, it is called *cloud computing*. IoT applications can then be integrated with a data analytics engine for analyzing and customizing the output.

2.1.2 Protocols and connectivity

The concretization of the IoT concept has been made possible by the introduction of communication protocols, the most significant of which are: WSN (Wireless Sensor Networks), used in particular for sensing operations (environmental sensors); RFID, a system based on the use of radio-frequency waves, consisting of tags, readers and a back-end system that allows each ID to be associated with the corresponding physical object and any information relating to it; the NFC protocol, produced by Philips, Sony and Nokia, used to transfer data from one device to another over short distances.

From these communication protocols, all the new standards we use today have developed, which we can group into two main classes, one short-range and one long-range. The short-range, low-power category is usually used for smaller environments such as homes or offices, which can be defined as Personal Area Networks (PAN). It includes technologies such as Bluetooth, NFC, Wi-Fi, Z-Wave and ZigBee. The long-range network category, on the other hand, allows communications up to 500 m with a minimum amount of energy. Within this category we find technologies such as LPWAN, from which proprietary solutions LoRaWAN and SigFox derive, as well as cellular IoT technologies such as NO-IoT, LTE-M and EC-GSM-IoT proposed by 3GPP.

Within a specific network, devices communicate according to a particular type of protocol, i.e. a set of rules that work on different layers of their reference model and according to which data is transmitted and received along Internet backbones. The IoT is thus to be understood as a network that lives in parallel to the traditional protocols used, for instance, for the web (fig. 3)

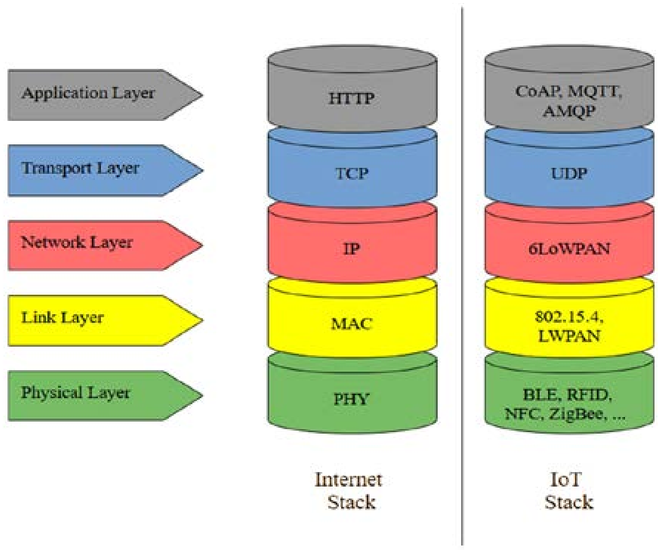

Fig. 3: IoT and Internet architecture

At the **application level**, that is, at the interface between user and device, we find the following protocols:

- CoAP (Constrained Application Protocol) (Shelby et al., 2014), a bandwidth and network constrained protocol designed to bring web functionality to devices with limited capacity. It uses a binary format rather than a text format like HTTP, for whose integration it requires the use of an intermediary (proxy);
- MQTT (Message Queue Telemetry Transport) (Banks et al., 2019), a messaging protocol designed for lightweight computer-to-computer communications, used primarily for low-bandwidth connections to remote locations. It uses an author-subscriber crtiteria and is ideal for small devices that require bandwidth efficiency and battery usage;
- AMQP (Advanced Message Queuing Protocol) (Godfrey et al., 2012), a specification for interoperable messaging for message-oriented middleware (MOM), creates interoperability between messaging middleware. It allows a wide range of systems and applications to interact, creating an asynchronous messaging system complementary to the http protocol.

The **transport layer** enables and protects the communication and transmission of data between different layers; within it we find:

- TCP (Transmission Control Protocol) (Eddy, 2022), the dominant protocol for most Internet connectivity. It provides host-to-host communications by splitting large data sets into individual packets and resending and reassembling packets as needed;
- UDP (User Datagram Protocol), a communication protocol that enables process-to-process communication and runs over IP. UDP improves data transfer rates over TCP and is optimal for applications that need lossless transmissions of information.

The **network layer** helps individual devices communicate with the router; in this layer we find:

- IP (Internet Protocol), many IoT protocols use IPv4, while newer implementations use IPv6. This recent IP update routes traffic over the Internet and identifies and locates devices on the network.
- 6LoWPAN (IPv6 over Low Power Wireless Personal Area Networks) (Kushalnagar et al., 2007), is an IoT protocol conforming to the IEEE 802.15.4 specification that works optimally with low-power devices with limited processing capabilities. It allows the creation of wireless networks with devices that use the IP protocol for communication, through an intermediate layer placed between the MAC and network layers.
- BACnet (Building Automation and Control Network), is a protocol developed by ASHRAE, and reported within ISO 16484-5, for managing building automation systems. Its goal is to create application protocols adaptable to all building control needs and transportable from one of the existing physical network technologies.

The **data layer** (MAC) is the part that transfers data within the system architecture, identifying and correcting errors found in the physical layer; within it we find:

- IEEE 802.15.4, an IEEE standard based on radio waves for a low-power wireless connection. It is used with Zigbee, 6LoWPAN and other standards to create embedded wireless networks;
- LPWAN, networks allow communication between distances of 500 meters to more than 10 km in some locations. They arise to meet the special needs of the many applications that require wider coverage but do not need high bit-rates. The LoRaWAN network, developed by the LoRa Alliance, is an example of an LPWAN network optimized for low power consumption.

Table 1: Most common IoT protocols

Protocol	Standard	Frequency	Distance
NFC	ISO/IEC 18092, ISO/IEC 21481, ISO/IEC 28361	13.56 MHz (universal frequency)	Max 10 cm (with other frequency you can obtain different distances)
Wi-Fi	802.11n (2009) – 802.11ac (2014)	2.4 GHz – 5GHz	50 m (indoor) – 100 m (outdoor)
BLE	Bluetooth v.5 (based on IEEE 802.15.1)	2.4 GHz	50 m
ZigBee	ZigBee 3.0 (based on IEEE 802.15.4)	2.4 GHz	10 – 100 m
Z-Wave	Z-Wave Alliance (proprietary technology)	800 – 900 MHz	10 m (indoor) – 100 m (outdoor)
6LoWPAN	Based on IEEE 802.15.4	Multiple physic support	20 m
LoRa	LoRaWAN (ITU-T Y.4480)	ISM 868/(915) MHz	10 km

The **physical layer** is the communication channel among devices in a specific environment; part of this layer are:
- Bluetooth, developed by Ericsson in 1994 and defined by the IEEE 802.15.1 standard, is an alternative to wireless information exchange using radio waves. It is optimal for high-speed data transfer up to 10 m. BLE (Bluetooth Low Energy) is a newer implementation that significantly reduces power consumption and cost while maintaining a connectivity range similar to that of classic Bluetooth;
- Ethernet, a wired connection that provides a fast data connection with low latency;
- LTE (Long-Term Evolution), a wireless broadband communication standard for mobile devices and data terminals. The LTE standard increases capacity and speed of wireless networks and supports multicast and broadcast streams;
- NFC (Near Field Communication), a set of communication protocols using electromagnetic fields that allows

two devices to communicate at a maximum distance of 4 cm. When the two devices are brought close together, a peer-to-peer network is created that allows both to exchange information. They are typically used for contactless payments for mobile devices, ticket creation and smart cards;
- PLC (Power Line Communication), communication technology that allows data to be sent and received over existing power cables. It allows an IoT device to be powered and controlled over the same cable;
- RFID (Radio Frequency IDentification), uses electromagnetic fields to track otherwise unpowered electronic tags. Compatible hardware provides power and communicates with those tags, reading their respective information for identification and authentication;
- Wi-Fi, standard 802.11, is a standard in homes and offices. It does not always fit all scenarios because of limited range and 24/7 power consumption;
- Z-Wave, mesh network that uses low-energy radio waves for appliance-to-appliance communication. Being a proprietary technology, it is based on a different architecture on all layers;
- Zigbee, developed by the ZigBee Alliance, now Connectivity Standards Alliance, IEEE 802.15.4-based specification for a suite of high-level communication protocols used to create personal local area networks with small, low-power digital radios. It is typically used in the context of the smart home where we find battery-powered devices. The total uptime is limited and most of the time the device is in a power-saving state (sleep mode);
- Thread, developed by Nest and other companies, is based on the 6LoWPAN protocol for a mesh connection;
- Matter, an open standard for the Smart Home developed by the Connectivity Standard Alliance with the aim of improving the compatibility and security of IoT devices.

2.2 BIM and IoT

In recent years, the massive development of digital technologies for acquiring data from variously deployed sensors for a multiplicity of uses and purposes, both within buildings and in the urban environment, has necessitated an expansion of the traditional semantic domains of the construction industry with particular reference to BIM-based information management processes (He et al., 2021; Tomalini, 2022). Created initially as a method for exchanging data between different silos, BIM today is increasingly being approached with concepts such as big data, IoT, and AI, which are seen as potential solutions for automation and inclusion of broader environmental contexts. The evolution of interoperability solutions, from ISO STEP to IFC to IFCOWL, is leading to the transformation of a static BIM to a new web-based paradigm.

In fact, the information model must be able to accommodate and store not only data-at-rest, produced in the survey and/or design phases, but also to manage data-in-motion, coming in real-time from devices for monitoring the environmental quality of architectural and urban spaces. However, the inclusion of IoT sensors within an asset should only be considered as a starting point for the implementation of a Digital Twin (Sacks et al., 2020). Indeed, there is no single DT solution, as this may vary from time to time based on specific needs, just as its implementation is subject to evolve over time.

Thus, the use of BIM methodology, and its extension to the Digital Twin concept, can bring enormous benefits for those involved in FM as it allows: planning of asset management systems and effective cost estimation; prediction of operational problems and improvement of maintenance activities; increased accessibility and security of information; reduced waste; and more reliable documentation (Singh et al., 2021). On the other hand, for IoT devices, many communication protocols and semantic models are available to support information exchange between devices but there is only partial integration with the IFC schema for the building.

For example, some studies have focused on integrating open protocols such as BACnet and the IFC schema, creating specific MVDs to represent BAS information within BIM models at different stages of the building process (Tang et al., 2020). Even the use of extensions to the IFC schema, however, is still an immature process and provides only limited support for the integration of this information (Wang et al., 2022). In addition, the IFC format is designed for transferring data from one tool to another and is therefore not meant to be dynamically modified or transformed. The definition of Linked Data (LD) and the Web Ontology Language (OWL) has recently tried to address these issues.

Given the limitations of the IFC schema some organizations have begun to develop alternative or complementary data schemes such as the Brick Schema, which provides a semantic description of the physical, logical, and virtual assets within a building and their relationships. This schema is defined using the Resource Description Framework (RDF) and is thus integrable with Semantic Web standards and Linked Open Data. Within it, classes such as sensor or plant-type equipment find broader description, and since version 1.3 the schema also includes support for linking Brick models and the sensor network with communication protocols such as BACnet, facilitating the achievement of a digital twin. An IFC model can contain within it a link to the Brick model via a unique identifier contained within the *IfcLibraryReference* instance, so that an external platform can retrieve information from both schemas.

3. A FRAMEWORK FOR APPLYING DIGITAL TWIN TO BUILT ASSETS

A processing framework is defined for the collection and management of data-in-motion from IoT and subsequent integration with data-at-rest allocated in a BIM-based common data environment, aimed at the creation of a Digital Twin of existing real estate assets, oriented to subsequent developments of big data analytics through AI applications. It is thus intended to support the decision-making processes of the different operators, owners, facility managers, technicians and experts involved in the operational phases of buildings and to be able to plan planned and/or corrective maintenance actions, generate content, recommendations, best practices and formulate forecasts on managed assets. Particular insight will then be conducted for the optimization of integration processes between BIM and IoT in relation to interoperability and data-set exchange issues in the creation of DTs, and to enable real-time visualization of monitoring data from BIM models for Facility Management.

The proposed approach involves the implementation of BIM models from the data and information held by the owner, which manages the real estate assets, whether of geometric (2D/3D), alphanumeric or documentary type, enriched with the additional semantic content useful for the subsequent management phases. Upstream of this operational phase, however, an in-depth analysis must be developed of the activities carried out within the same estate property concerning the maintenance and functionality of the assets in terms of actions carried out, resources and available infrastructure, aiming to define the organization's information requirements (OIR), to which all the information exchanges that will govern the various management processes must be informed. This should converge in the compilation of a BIM Guide for the implementation of the organization's asset information models, which can standardize their delivery processes among the various internal operators, or external suppliers, following specific standards and best practices adopted by the company.

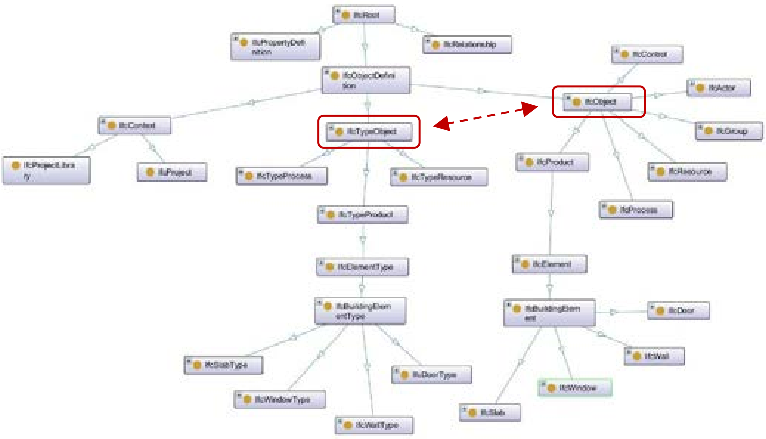

Fig. 4: Derivation path of IfcObject and IfcTypeObject inside IFC schema

The addressee of this research is a public institution and consequently it is necessary to think not only in terms of proprietary formats but how the various building elements and their information should be modelled and delivered to the maintainer. After compiling the OIRs the next step is therefore to draw up matrices based on the Level of Information Need concept that allow us to catalogue all the assets within individual buildings so that we have a complete technical record of the minimum information to populate our models. This also allows us to begin to create a library of general BIM objects that can be used in any building, and associate to each of these the relative class of the IFC schema with the appropriate psets necessary to convey the required information. A first reasoning must be made on the naming convention to be adopted for the creation and use of such objects, since if we look at the proprietary Revit software, for example, we find the distinction between family name and type name, while within an IFC model we can observe many instances of the same object (*IfcObject*), each with its own name, typically distinguished by a progressive number, and different types (*IfcTypeObject*) which instead perform the function of template for the assignment of homogeneous parameters for that grouping of objects (fig. 4). Types and instances in this case are both derived from the superclass *IfcObjectDefinition* and therefore have a horizontal relationship with cardinality [1:N] and not a vertical dependency as proposed by proprietary software. This entails the assignment of different names as the former must be understood in a generic context regardless of the project (*IfcProject*) in which they are placed, while the latter have their own identity when placed within a floor (*IfcBuildingStorey*), or a room (*IfcSpace*), and consequently are assumed to require, in a management type environment, a code capable of representing this position and not being generic for the whole building. The second reasoning must then be done on the parameters relating to these entities. Finding a correspondence between the parameters already in use by an organisation and those prepared by the IFC schema is not always trivial or easily represented by the tools in use today. Where it is not possible to find this relationship, in fact, custom psets created within the BIM authoring software will be used to meet the needs of the client, knowing that they may be subject to change over the years as a result of future changes to the schema proposed by buildingSMART.

In parallel, a data environment will be set up to collect, index and process data from a number of IoT devices deployed within the assets (Fig. 5). These devices are to be chosen based on the observations presented in the previous chapters and will need to enable real-time collection of environmental, or other designated, information. There will then be a breakdown by layers, where the physical layer will be represented by the device itself; the latter will send the collected data to one or more gateways, or directly to the cloud, for indexing and aggregation of the information (Data Storage Layer). Then the data, depending on the type, can be integrated within appropriate databases (Data Integration Layer) and retrieved through appropriate processes or APIs within software applications for real-time analysis and querying.

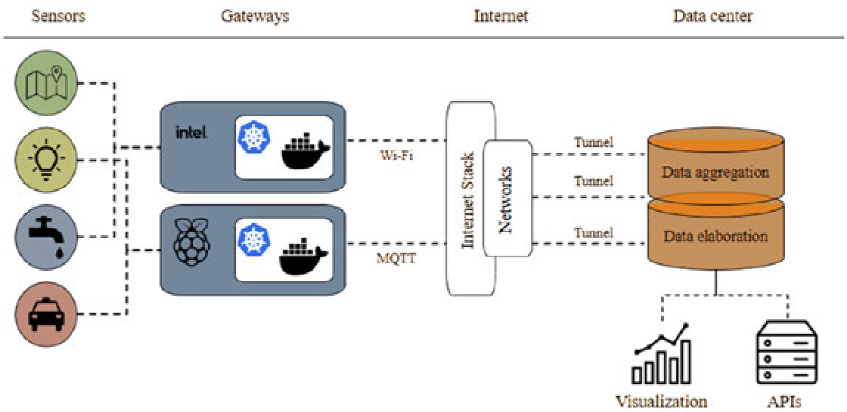

Fig. 5: IoT framework

Aware of the impossibility of directly integrating dynamic information within a BIM model, and in particular within the IFC schema, it is necessary to adopt an intermediate platform that acts as a collection and processing point for all the data collected. The workflow envisages the inclusion within the BIM models of digital representations of the sensors (*IfcSensors*) that will be inserted into the real environment with a series of parameters describing their characteristics and the use of a unique identifier (*IfcTag*) that can be used as a key for association with external DBs. This reference must necessarily be the same as the one present in the DB created from the data collected by the various sensors. The use of a cloud-based platform finally allows us to combine these two databases, representative of two different semantic domains, for the creation of customised queries and dashboards useful for the maintenance of an entire portfolio of assets.

3.1 The case studies

A PNR EU Next Generation research project, entitled *"BIM-to-Digital Twin: information management to support decision-making in the building life cycle"*, has been initiated as part of a collaboration with the University of Florence's Building Area, with the aim of developing information management of built assets belonging to the university's real estate stock through the implementation of BIM information models aimed at facility management.

The Building Area is divided into three Process Units - Real Estate, Building Plan, Ordinary Maintenance - in addition to Administrative Support, to which are added two specialized services called "Fire System Management (GSA)" and "Control and Maintenance of Asbestos Containing Materials". In particular, the tasks of the Ordinary Maintenance PU are those of planning and scheduling of ordinary maintenance interventions, coordination of technical referents allocated in the various territorial offices, monitoring the need for programmable maintenance interventions and requests for urgent interventions, and coordination with the Property and Logistics Services Area in cases of integrated interventions.

Facility management operational services managed by Ordinary Maintenance UP are divided into: 1) Maintenance services, 2) Cleaning and environmental hygiene services, and 3) Reception and porterage services. Each operational service includes various activities that are divided into: ordinary activities (predefined or supplementary) or extraordinary activities (breakdown or on-demand). Maintenance Services include all activities aimed at maintaining the functional state and preservation of the building's systems and construction components. Specifically, the categories of systems managed as different maintenance services are the following: Electrical system, Water system, Heating system, Air-conditioning system. Elevator system, Firefighting system, Security and access control system, Networks, Minute building maintenance.

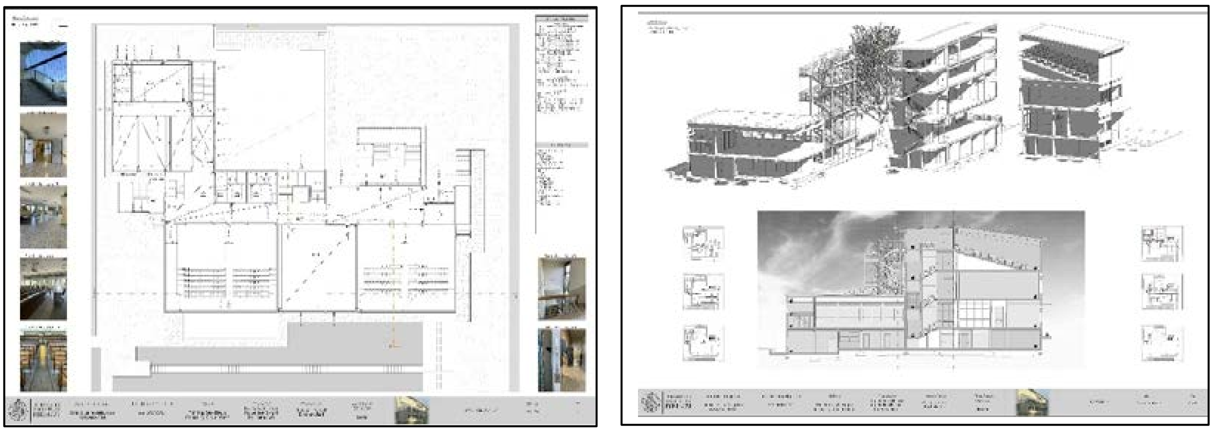

Fig. 6: Layout from BIM model of an asset of University of Florence

The managed real estate portfolio is characterized by numerous assets, different both in terms of function, construction, system, etc., and historical-architectural value, which require different intervention methodologies and maintenance systems from case to case. Precisely with regard to management and maintenance processes, the University has been equipped for some years now with a dedicated IT tool for the management of its real estate assets, namely Infocad.FM by Descor s.r.l., a corporate partner in this research. The backbone of this tool is the centralized and standardized Technical Registry within which all the information (documents, data sheets, CAD plans, photos, etc.) used, by those who interact in various capacities with the properties, converge.

The buildings in the archives are subdivided by municipality and geographical area. Each building is also currently accompanied by all the patrimonial and urban planning documentation that distinguishes it (cadastral extracts, property titles, lease or loan contracts, etc.). Despite this rationalization effort there are still many difficulties in the information management of these assets mainly due to the heterogeneity of the available data and information, since in many cases these documents are still in paper format. Therefore, there is a need to move to an information management using BIM tools and methodologies, so that data and information about the building are produced, managed, stored and exchanged in a secure, reliable and consistent way within a CDE, which allows not only the uploading of files but also the writing of metadata related to them (Paparella & Zanchetta, 2020).

The launch of the research project saw the selection of pilot cases and the implementation of a number of built asset information models, which will serve as the test bed for the testing of IoT models and the subsequent development of Business Intelligence (BI) to support facility management activities. Specifically, the asset model of each building is organized into federated models related to the different disciplinary domains-architectural, structural, and systems to facilitate the management of the model's information content in the subsequent stages of data extraction for technical performance simulation (fig. 6). The various modeling stages are developed depending on the type of geospatial data available through CAD-to-BIM and/or Scan-to-BIM processes and through the use of Autodesk Revit BIM authoring software, which will be followed by export to IFC format, mapping all elements to the correct schema class.

A phase of analysis of the history of the maintenance actions carried out by the Ordinary Maintenance UP and the related costs incurred for each building investigated is also underway, in order to define strategic lines of improvement in the FM of the managed assets to be conducted through the preparation of an IoT model for environmental monitoring, energy consumption and in general the efficiency of the facilities. In particular, this will make it possible to identify those spaces within the buildings that, in relation to their conditions of use, can be a source of useful data to be acquired by sensors (temperature, humidity, pressure, air quality, movement, brightness, etc.).

4. CONCLUSIONS AND FUTURE DEVELOPMENTS

The use of BIM tools and methodologies in the information management of the operational phases of a built asset with its extension to the Digital Twin concept can bring enormous advantages from an economic and management perspective for the owner entity and more specifically for facility managers.

The "BIM-to-Digital Twin" research project, to date in its start-up phase, aims to implement a Decision Support System (DSS) within Facility Management activities through the integration of BIM platforms and IoT technology, geared toward subsequent developments of big data analytics and AI applications. The system should accommodate different types of structured and unstructured data from different sources and enable integration with the IoT model identified for the specific experimentation conducted in the various case studies identified.

This contribution aimed to develop a broad survey of the various approaches available and the problem still open for defining an information technology architecture, which supports the implementation of IoT sensors that can be integrated with the BIM information models of built assets for more efficient management of maintenance and operation activities implemented by owners. Despite the wide variety of communication protocols and semantic models for information exchange between IoT devices there is still only partial integration with the IFC scheme for building classification. Extensions of the IFC schema still provide immature and limited support processes in integrating this type of data. In fact, the IFC format was not designed for data-in-motion transfer from one tool to another and thus to be dynamically modified. The definition of Linked Data (LD) and the Web Ontology Language (OWL) has recently tried to address these issues.

Promising developments can be recognized in the Brick Schema where within it classes such as sensor or plant-type equipment find wide description, and connections between Brick models and the sensor network with specific communication protocols are also included, facilitating the implementation of Digital Twins.

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COMBINING LARGE-SCALE 3D METROLOGY AND MIXED REALITY FOR ASSEMBLY QUALITY CONTROL IN MODULAR CONSTRUCTION

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ABSTRACT: *The quality control (QC) of assembled modules is an essential process when constructing modular buildings such as hotels and hospitals. Defects that go undetected during module assembly may result in lost productivity in the form of unnecessary transportation, rework or project delays. QC has traditionally been performed using specialized tools and carried out a posteriori in an inspection station dedicated solely to this task. Nowadays, large-scale 3D metrology technology provides a more efficient alternative since it enables accurate measurements to be taken* in situ*. Additionally, mixed reality (MR) supports the immersive projection of information and guidance instructions. This paper introduces a proof of concept of a framework that combines industrial photogrammetry with the HoloLens 2 MR headset to assist with assembly and QC during the off-site construction phase of modular construction. Many tests were conducted in a laboratory and a factory setting to evaluate the system's user-friendliness and possible challenges associated with its future implementation. The experiments conducted confirmed that combining 3D metrology with MR offers an interesting solution for integrating QC into the assembly process. However, further work is needed to enhance the measurement workflow and optimize the measurement system's accuracy.*

KEYWORDS: *3D Metrology, Augmented Reality, Mixed Reality, Modular Construction, Photogrammetry.*

1. INTRODUCTION

In modular construction, volumetric building units, or modules, are factory-built with almost complete interiors including plumbing, electricity, insulation and even furniture. They are then transported to the construction site for final building assembly, which basically involves stacking the pre-assembled modules together. The modules' structure can be made of wood, steel or a combination thereof depending on the customer's requirements and the final height of the assembled building.

During module assembly in the factory, the control of key characteristics (e.g., overall dimensions, squareness error, parallelism of the ceiling and floor) is essential to ensure the module complies with the specifications and estimate the adjustment shims needed when stacking modules on-site. Traditionally, this process has been carried out manually using tools like measuring tapes and levels in the assembly stage and controlled *a posteriori* at an inspection station dedicated solely to this task. If necessary, adjustments and corrections are then made, which leads to lost productivity in the form of unnecessary transportation, rework or project delays.

The advent of contactless 3D metrology provides a valuable alternative since it makes it possible to take accurate measurements *in situ,* while building information modeling (BIM) provides a 3D digital representation of as-designed buildings. This combination of technologies thus automates inspection and digitalizes QC information. QC automation in the prefabricated construction industry has been addressed in recent research. Bae and Han (2021) proposed a vision-based approach to off-site quality inspection that reconstructs 3D point clouds using a projector camera system and computes how much scans deviate from the virtual model to generate quality assessment error maps. Kim et al. (2019) proposed to use a registration-free mirror-aided laser scanning approach to inspect the dimensions and geometric requirements of planar prefabricated elements. Xu, Kang, and Lu (2020) used laser scanning reconstruction technology to inspect surface defects in prefabricated concrete elements. The information they collected during QC was then stored in accordance with the Industry Foundation Classes (IFC) standard and integrated in a BIM platform.

In industry, advances in 3D measurement systems have made it possible to incorporate inspection in the assembly process, which is referred to as measurement-assisted assembly (MAA). The term MAA is used to describe any process that involves measurements being used to guide assembly and QC (Muelaner, Kayani, Martin, & Maropoulos, 2011)

MAA was first introduced as a paradigm shift for the assembly of high-quality large-scale complex structures like aircraft frames to eliminate the monolithic jigs and manual specialized tools that were usually involved in large

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Wafa Bounaouara, Louis Rivest, Antoine Tahan, *Combining Large-Scale 3D Metrology and Mixed Reality for Assembly Quality Control in Modular Construction,* pp. 1171-1180, DOI 10.36253/979-12-215-0289-3.116

flexible-component assembly (Maropoulos, Muelaner, Summers, & Martin, 2014). This paradigm shift was motivated by advances in large-scale 3D metrology systems that made it possible to take measurements during fabrication or *in situ.* This is particularly beneficial because large-scale structures are often too big to fit into conventional measuring devices or be transported to calibration laboratories (Schmitt et al., 2016). While the construction industry requires less accuracy than the aerospace industry, the same concept can be used to integrate QC in the assembly process of modular and prefabricated structures.

On the other hand, workers need to keep their hands free during assembly to move around and carry their tools. Augmented reality (AR) and mixed reality (MR) technology can make a significant contribution here. They merge computer-generated information with real-world sensations using a device (e.g., a head-mounted screen, a projector, or a tablet) that provides an immersive user experience and eliminates the need to constantly look at fixed screens for information. In the case of MR, the user can interact with the virtual objects (Peddie, 2017). MR can be seen as an evolution of AR that has been made possible by technological advances in sensors and imaging techniques (Park, Bokijonov, & Choi, 2021).

Various studies have evaluated applying AR and MR to assembly tasks and inspection processes. Qin et al. (2021) investigated whether it was possible to use head-mounted AR displays for wood frame assembly tasks. Ahn, Han, and Al-Hussein (2019) proposed to use a projection-based AR system to provide workers with visual guidance during manual panel assembly. Their system projected as-designed models (panel drawings) into the assembly station. Kwiatek et al. (2019) demonstrated that using a mobile AR application in conjunction with 3D scanning during pipe section assembly and inspection improved productivity, reduced the amount of work that needed to be redone, and enhanced workers' spatial skills. Talamas (2017) evaluated using MR interfaces to automate the metrology process flow for in-line assembly process inspection and found that each volunteer made fewer errors when using the MR interface than paper or laptop instruction guides.

The aim of this paper is to propose a proof of concept of a framework that combines 3D measurement technology and MR to integrate QC in off-site module structure assembly. The purpose is to enhance productivity during the assembly process, provide more accurate measurements, and ensure quality output traceability.

2. MATERIALS AND METHODS

2.1 Measurement Equipment

In this research, we focus on assembling a cuboid wood frame structure formed of a floor, four walls and a ceiling. We suppose that the quality of these six parts was previously controlled. To control the quality of the assembly process, we measure the 3D position of a set of points that will make it possible to control the key characteristics, (KCs) the overall dimensions, squareness error, parallelism of the ceiling and floor, etc. These positions will then be compared to the data represented in the computer-aided design (CAD) model. Fig. 1 illustrates the wood frame structure and the set of control points.

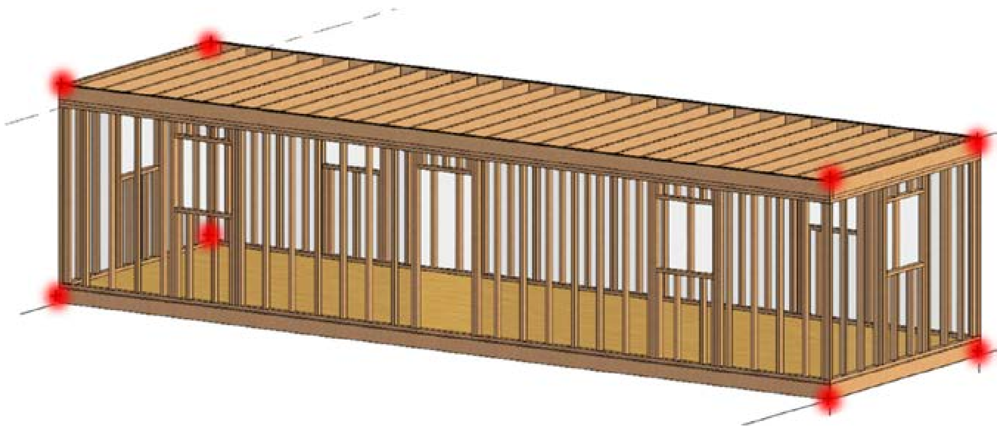


Fig. 1: Wood frame structure

Photogrammetry is a technology that is based on the principle of optical triangulation. An element is positioned in 3D space by at least two cameras that are used to identify targets from different viewpoints. The targets reflect infrared light. The cameras can then capture the position of the targets and position them in relation to the measurement system reference. Multiple targets can be perceived simultaneously, and their positions can be determined dynamically for real-time target tracking (≥ 10 Hz). Photogrammetry is used in many sectors for dimensional inspection. In our research, we use its tracking capability to provide 3D measurement data to assist with the assembly process. C-Track is a photogrammetry device from the company Creaform® that has a measurement volume of up to 16 m^3. Its measurement range can be extended by combining up to four devices to form a measuring system around assembly stations. This eliminates the need to transport measuring equipment from one station to another. Additionally, C-Track can be integrated with portable scanners to probe or scan specific geometric elements as required.

However, the retroreflective targets that are commonly used with C-Track, such as stickers and magnetic artifacts, are unsuitable for wood framing and cannot be accurately calibrated in the CAD model. To address this limitation, customized artifacts have been developed. The artifacts are designed to be easily attached to a wood frame. Each artifact is composed of three retroreflective targets (C1, C2, C3) to locate a point in 3D space. The targets have different spacing to be able to easily differentiate them. Fig. 2 shows a sample artifact developed for tracking the upper corner of a wall.

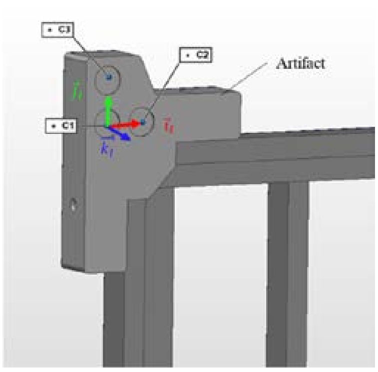


Fig. 2: Sample artifact

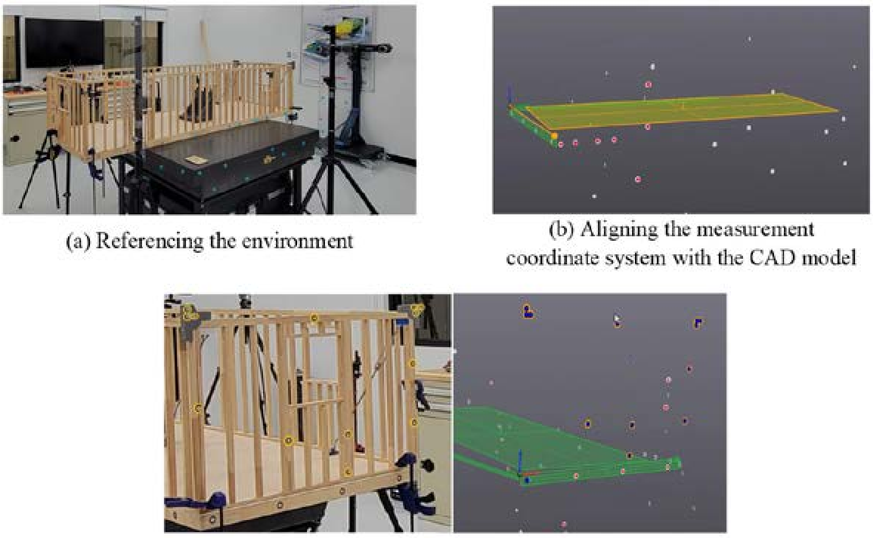
2.2 Measurement System Setup

Prior to initiating the inspection process, certain preliminary operations must be conducted to prepare the measurement system. These operations are: environmental referencing, alignment (or registration), and tracking model creation.

Environmental referencing: This step serves to establish a frame of reference for C-Track within the real environment. The working environment is identified using retroreflective targets (the targets shown in blue in Fig. *3* (a)). These targets are then registered using the primary C-Track (if multiple C-Tracks are used) and exported as a reference file. Once this has been done, measurements can be taken by moving C-Track within the referenced environment.

Alignment: To be able to compare measured point coordinates with the CAD model, the C-Track needs to be aligned within the 3D CAD volume. This involves creating reference entities that align the instrument in the metrology software workspace with the real-world instrument. We utilized the floor as a centerpiece. Three perpendicular planes were probed and used to define the measurement coordinate system (as illustrated in Fig. *3* (b)), which was then aligned with the CAD model. Creaform's HandyPROBE portable probe was used with C-Track for this alignment process.

Tracking model creation: The tracking model refers to the collection of retroreflective targets that the C-Track system dynamically tracks. To create this model, the targets comprising the tracked artifacts are registered using the C-Track. Fig. *3* (c) illustrates this process. The acquired targets are then exported as a text file for future use during the inspection process.



(a) Referencing the environment

(b) Aligning the measurement coordinate system with the CAD model

(c) Creating the tracking model

Fig. 3: Measurement system setup

2.3 Data Processing

The raw data collected by C-Track has to be processed and interpreted in order to extract KCs and interpret the measurements in line with the technical specifications. VxElements® software was used with C-Track for data acquisition. For data post-processing, inspection software offers a wider range of tools. In this project, PolyWorks Inspector® was used to extract dimensions from a CAD model, import measurement data and compare the measurement data with the CAD data. Moreover, macro scripting was used to automate the dynamic measurement process workflow.

For each artifact (see Fig. 2), C-Track provides the (x, y, z) positions of the three targets (C1, C2, C3). It is thus possible to create a local coordinate system (ℓ) attached to the artifact. Once the geometry of the artifact is known, the position of a point of interest (for example, an upper corner of a wall) can be determined in the local coordinate system. Geometric transformation makes it possible to determine the point of interest's position in the global coordinate system (the measurement coordinate system). This logic is computed via macro scripts in PolyWorks Inspector®. The detailed method is explained below.

The first step is to identify the targets, which involves associating them with each point of interest and distinguishing each artifact's different targets. To identify the targets that correspond to each artifact, we calculate the Euclidean distances between the nominal position of the corresponding point of interest and the targets. The three targets that lie within a sphere of radius 10 cm around a point of interest are considered the targets associated with the relevant artifact. If one or more targets are missing, an error message is displayed. This approach is based on the assumption that the part (the wall, for example) is positioned roughly at its nominal (CAD) position. Once the three targets associated with each artifact have been identified, the three targets are distinguished by comparing the distances between the targets based on the artifact's geometry. Equation 2.1 provides the vector calculations for creating a local coordinate system $\ell(\vec{\imath}_\ell, \vec{\jmath}_\ell, \vec{k}_\ell)$ around each artifact using the positions of the three targets (C1, C2, C3).

$$\vec{\imath}_\ell = \frac{C_2 - C_1}{\| C_2 - C_1 \|}; \ \vec{\jmath}_\ell = \frac{C_3 - C_1}{\| C_3 - C_1 \|}; \ \overrightarrow{k_\ell} = \vec{\imath}_\ell \wedge \vec{\jmath}_\ell \qquad 2.1$$

The position of the point of interest in the global coordinate system g, $P_g = (x_g, y_g, z_g)$, is calculated by geometric transformation from the position of the point of interest in the local coordinate system ℓ ($P_\ell = (x_\ell, y_\ell, z_\ell)$). This transformation is represented by Equation 2.2:

$$P_g = \mathrm{T}_{g/\ell} \cdot P_\ell \quad 2.2$$

where $T_{g/\ell}$ is the transformation matrix from the local coordinate system (ℓ) to the global coordinate system (g). To represent this transformation using homogeneous coordinates, Equation 2.2 is equivalently expressed as Equation 2.3:

$$\begin{Bmatrix} x_g \\ y_g \\ z_g \\ 1 \end{Bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{Bmatrix} x_l \\ y_l \\ z_l \\ 1 \end{Bmatrix} \quad 2.3$$

Equation 2.4 donates the rotation matrix:

$$\begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} = \begin{bmatrix} x\vec{\imath}_g & x\vec{\jmath}_g & x\vec{k}_g \\ y\vec{\imath}_g & y\vec{\jmath}_g & y\vec{k}_g \\ z\vec{\imath}_g & z\vec{\jmath}_g & z\vec{k}_g \end{bmatrix} \quad 2.4$$

The translation vector corresponds to the coordinate of the origin of the local coordinate system in the global coordinate system as donated by Equation 3.1:

$$\begin{Bmatrix} t_x \\ t_y \\ t_z \end{Bmatrix} = \begin{Bmatrix} xc1_g \\ yc1_g \\ zc1_g \end{Bmatrix} \quad 2.5$$

2.4 User Interface

As mentioned above, this project uses MR to project dynamic measurements for a user during wood frame structure assembly. The HoloLens 2 headset is a completely standalone head-mounted display (HMD), which means that it doesn't need to be connected to a separate computing device. In addition, it is MR-based, which means that it enables users to interact in real time with digital content that is superimposed on the real world. The content takes the form of holograms, and the holograms interact simultaneously with the user and the real world. Furthermore, HoloLens 2 enables users to interact with holograms using voice commands, hand gestures or eye movement. What's more, the technology makes it possible for two users in different locations to see what the other sees, which enables one to guide the other through a process or simply interact with the world the other sees. This feature has the potential to make remote collaboration easier, more efficient and far more interactive. In addition, an MR plug-in exists for PolyWorks Inspector that makes it possible to manipulate an inspection project directly on HoloLens 2. Macro scripting can also be used to customize the user interface displayed by HoloLens 2.

The user interface must provide the operator with the values of the KCs measured to guide the adjustments to be made and ensure the geometric quality of the assembly. In addition, it must enable the operator to perform certain control commands, such as exporting results and navigating between different inspection stages.

The user interface proposed has two components (Fig. 4): (i) the menu or toolbar, which is composed of three buttons that are each associated with a command Button 1 launches dynamic measurement, Button 2 exports the measurement results, and Button 3 shows or hides the CAD hologram; and (ii) annotations to display the measured value's deviation from the nominal value along the x, y and z axes. The annotations are displayed at the nominal position of the corresponding point of interest and change color depending on whether the measured value is within or outside of the tolerance interval. Note that the functionalities of the PolyWorks AR plug-in for HoloLens 2 were used to align the CAD hologram with the real environment.

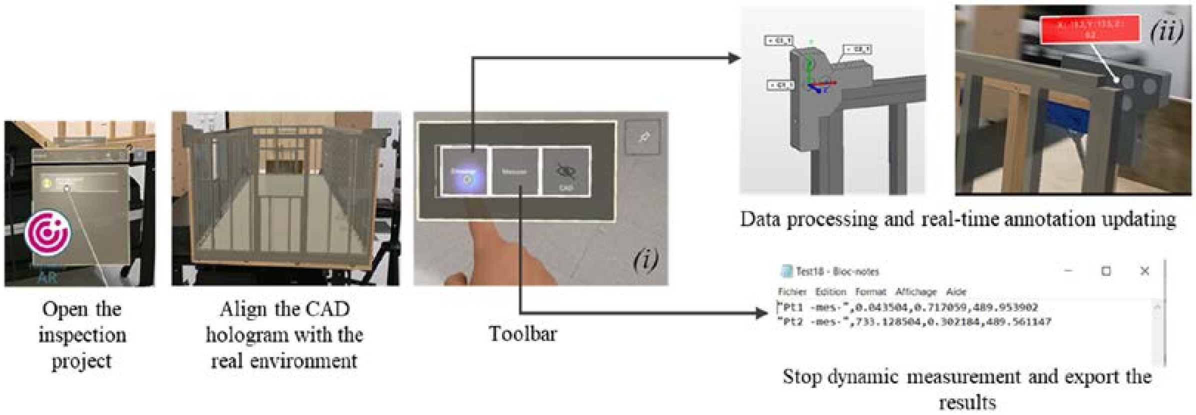


Fig. 4: User interface created for the HoloLens 2 headset

3. LABORATORY TESTING

In order to conduct tests in a laboratory setting, a scaled-down module had to be constructed that adhered to spatial and ergonomic limitations. The scaled module replicates a typical wood frame structure and is around 1/8th the size of an actual module. The module was designed using CAD software. Dimensional and geometric data was present in the CAD model and served as reference information for the nominal (as-designed) model. The measured data was subsequently compared with this nominal data.

3.1 Experimental Setup

The floor was placed on a granite surface plate and secured to the table with a weight to prevent it from moving (see the picture on the right in Fig. 5). Next, we acquired the reference targets, performed alignment and acquired the tracking model as explained in § 2.2.

In an industrial context, adjustable braces are used while assembling walls. A turnbuckle system was built to replicate this for the experiment and allow the operator to easily adjust the position of the wall while tracking the position of the point of interest (see the picture on the left in Fig. 5).

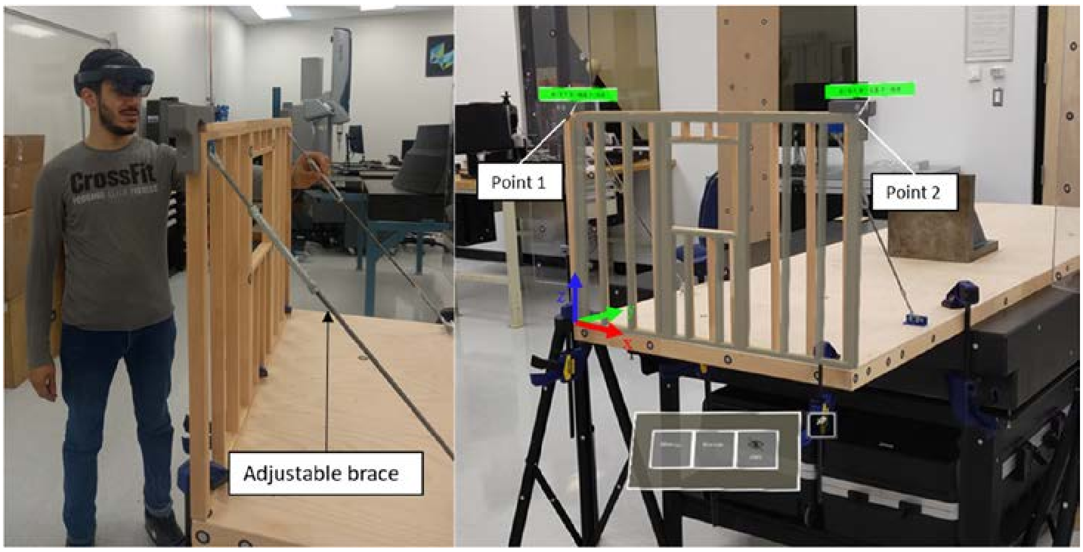


Fig. 5: Experimental setup

3.2 Gage Repeatability and Reproducibility Study

A measurement may be influenced by various sources of variation during the inspection process, which results in there being uncertainty associated with each measurement result. Measurement uncertainty is a quantitative assessment of the unreliability associated with a measurement result based on probability distributions. The dispersion of a set of measurements of a quantity can be characterized using the estimator of its standard deviation, which is also known as standard uncertainty (σ).

Studying the overall uncertainty of the measurement system and evaluating whether the system is able to accurately detect quality defects requires more in-depth study that is beyond the scope of this project. In this study, we intend only to evaluate the amount of variation in the measurement data that is attributable to the measurement system in the configuration proposed. Measurement system variation consists of two important factors, repeatability and reproducibility (R&R). Repeatability is related to equipment variation, whereas reproducibility is related to inspector or operator variation. Measurement system variation can be assessed by conducting a Gage R&R study, which involves data being collected by having multiple operators measure the same set of parts in a random order. Several methodologies can be used for statistical analysis of the data obtained from the Gage R&R study. We chose to use the ANOVA method, which breaks down the sources of measurement system variation as follows:(1) part-to-part: variation originating from the parts being studied; (2) reproducibility: variation originating from the operator(s); (3) operator/part: variation arising from the operator(s) interacting with the parts; and (4) repeatability: variation that originates from the measuring system and cannot be attributable to other sources of variation. The purpose of measuring multiple parts is to evaluate manufacturing method variation, which is also beyond the scope of our research. Therefore, only one part is measured in this study and, thus, variation sources (1) and (3) listed above (which are usually provided by ANOVA) are not taken into consideration in our analysis results.

3.3 Test Sequence

Two operators were asked to repeat the positioning of a wall while tracking the position of the wall's two upper corners. An operator begins by wearing the MR headset and opening the project. The interface displays a hologram of the CAD file with the wall in its nominal position along with a three-button menu, the latter of which is described in § 2.4. The operator then positions the wall approximately in its nominal position and attaches it to the floor and the adjustable assembly brace system. They then fasten the artifacts to the top corners of the wall. Afterwards, they start dynamic measurement by pressing Button 1. The annotations are displayed to indicate each point of interest's positioning error on the x, y and z axes.

The operator begins by adjusting the wall's position along the x-axis in accordance with the deviation values displayed in the annotations for Points 1 and 2 (see Fig. 5). Once the x coordinate is within tolerance, the operator adjusts the position of Point 1 along the y and z axes by adjusting the adjustable brace. When Point 1's position is within tolerance along all three axes, the annotation changes from red to green. The operator then moves on to Point 2 and adjusts its position along the y and z axes. Once both annotations are green (see Fig. 5), the operator stops dynamic measurement by pressing Button 2, which automatically exports the values to a text file. Each operator repeated the sequence 37 times, with six measurements captured each time: *Point1_x*, *Point1_y*, *Point1_z*, *Point2_x*, *Point 2_y* and *Point2 _z*.

3.4 Results and Discussion

The data collected was analyzed using the ANOVA method. Table 1 indicates the repeatability and reproducibility standard deviation of x, y and z for Points 1 and 2. The precision-to-tolerance ratio P/T is expressed by Equation 3.1:

$$P/T = \frac{6\sigma}{USL - LSL} \qquad 3.1$$

where USL is the upper specification limit, LSL is the lower specification limit, and σ is the standard deviation of the measurement error.

Table 1: Gage R&R results

	Point 1			Point 2		
	x	y	z	x	y	z
$\sigma_{\text{repeatability}}$	0.335	0.487	0.152	0.325	0.413	0.089
$\sigma_{\text{reproducibility}}$	0.000	0.019	0.028	0.000	0.237	0.029
$\sigma_{\text{R\&R}}$	0.335	0.487	0.154	0.325	0.476	0.093
P/T	33.5%	49%	15%	33%	48%	9%

The results show that the maximum total standard deviation is 0.487 mm. This means that 95% of the time, the measurement value varies by no more than $4\sigma_{\text{Total}}$ = 1.948 mm ($\pm 2\sigma_{\text{Total}}$ = ±0.974 mm), which is below the maximum allowed tolerance range of 6 mm (±3 mm) indicated in the technical specification. However, for a measurement system to be considered “good”, its precision-to-tolerance ratio must be ≤10%. (Note that 10%<P/T≤30% is borderline, and P/T>30% is unacceptable).

It should be noted, however, that system variation is influenced by the fact that the operator is asked to position each point within an interval of ±1 mm. This can be confirmed by the fact there is less variation along the axis-z since this value is the least impacted by the positioning interval. In fact, when the operator adjusts the braces, the wall’s position along the z-axis almost doesn’t change. In addition, given the experimental setup, the y-axis corresponds to C-Track’s depth axis. A study of the effect C-Track’s depth of field has on measurement system variation showed that the depth of field has a significant effect on system repeatability (Émond-Girard, 2022). In all cases, the system repeatability error is greater than the reproducibility error, which means that the greatest source of variation is the measurement system itself, not operator manipulation.

4. FACTORY TESTING

In order to assess the user-friendliness of the proposed system and to highlight potential constraints linked to its use in an industrial environment, a test was carried out under real working conditions. Below is a description of the experimental setup and test procedure used, as well as the findings and observations noted following the test.

4.1 Experimental Setup and Test Sequence

A near-real-size module was designed to perform factory testing. The artifacts were also adjusted to a true scale. All system setup steps, including referencing the environment, aligning the measurement system with the CAD model’s global coordinate system, creating the tracking model, and aligning the CAD hologram with the real environment were first completed by the research team. Then, we explained to the operators assigned to take part in the tests how the system worked. Three (3) operators then worked together to pre-assemble the module and add the adjustable wall braces. One operator attached the artifacts and put on the MR headset to begin positioning the wall beginning with Point 1. Since the annotation displayed on the MR headset was small, the operator had to climb a ladder to read the value. The other two operators adjusted the position of the wall following the instructions given by the operator wearing the MR headset. The process was repeated until the position of Point 1 was within the desired tolerance range. The process was then repeated for Point 2 following the same procedure. Fig. 6 shows the test sequence.

Fig. 6: Factory testing sequence

4.2 Observations and Discussion

The preliminary actions involved in referencing the environment can be quite demanding in an industrial context. The referencing targets that C-Track requires to locate itself may move due to vibration and operator movement. In addition, during the assembly stage, the floor often moved (drilling of the floor to fix the adjustable wall braces, operator movement, etc.), which made the proposed registration method (alignment of measured data and CAD data) not well suited to the real context. The operator who used the HoloLens 2 headset reported that it was easy to use and comfortable to wear and work with. However, during the test, some drawbacks were noted with the user interface, such as the size of the annotations, which was deemed to be too small. Also, we had to explain to the operator the orientation of the axes and how to interpret the values displayed in the annotation because the coordinate system axes and displacement vectors were not indicated.

5. CONCLUSION

In this research, we were able to achieve a proof of concept of a system that combines industrial photogrammetry and MR to assist operators during the assembly of a wood frame structure. Points of interests were tracked and compared to the nominal data presented in the CAD model. The deviation between the nominal value and the measured value was projected on the real assembly through the MR headset. The proposed solution also supported the documenting of measurement results.

Although the Gage R&R study results showed that the measurement system varied less than the allowed tolerance range indicated in the technical specification, its precision-to-tolerance ratio is still higher than what is recommended. The error associated with artifact fabrication can contribute significantly to the system's variation; thus, further research should work on optimizing the artifact and using the artifact's as-manufactured geometry when computing the measurement data to minimize the amount of variation generated by the artifacts. Further research must be done to evaluate the measurement system's overall uncertainty and validate the system's ability to detect nonconformities.

The test completed in the industrial context helped to identify some drawbacks related to the proposed solution, and, thus, this research serves as a guideline for potential future implementation of a quality control system that combines 3D metrology and MR for integration in an assembly process.

The proposed measurement setup was complex and time-consuming, and keeping the reference targets stable seemed to be a struggle during factory testing. In order to use photogrammetry in *in situ* measurement-assisted assembly, fixed reference entity has to be integrated in the plant layout. Other large-scale technologies like indoor global positioning system (iGPS) could be investigated as an alternative type of measurement equipment. Also, improvements could be made to the user interface to provide the operator with more visual guidance and a more ergonomic way to display the measured values could be sought.

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BUILDING'S TWIN RECONSTRUCTION

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ABSTRACT: *The work shows a process that starts from the digitization of cultural heritage and through analysis arrives at the subsequent diachronic holographic representation. The object of the study was the creation of two holograms of historical buildings: the church of St. Maria in Sovana with an interesting subsoil and the ruin of church of St. Francesco, attributed to Sangallo il Giovane in Pitigliano. However, the theoretical setting of the research is placed at due distance from the twin term. It has implications and meaning that are not matched by producing a digital copy, even a very high resolution one. The use of different cognitive technologies and the assembly of the various inputs in a digital model can never be defined as a twin of the original. Bearing in mind what has just been specified, the work was organized according to different levels of acquisition of cognitive data. Obtained from the survey and from historical studies the shape of the original state, a historical narrative interweaving of digital models has been created. The hologram is a three-dimensional and dynamic representation, which in the case of the church of San Francesco shows the reconstruction of the ancient architectural complex, visualizing the evolution of the studies of historical documents, up to the vision of today's ruin. For the church of S. Maria, the underground area is reconstructed through the geoelectric analysis of the subsoil and of the urban composition. Use of high detection technologies (GPR and HVNSR). The holographic of the artifact, promotes scientific divulgation and its dissemination sharing experience, it is not realized through device indeed, but thanks a holographic display.*

KEYWORDS: *Digital twining of cultural heritage, hologram technology, scientific divulgation, dissemination - Diocesan Museum Palazzo Orsini of Pitigliano (GR).*

1. INTRODUCTION

The research activity concerning the case of the church of St. Maria in Sovana (GR) and the ruins of the church of St. Francesco in Pitigliano (GR) starts by questioning the real possibility of making a digital twin of any object or structure especially in relation to the concept of cultural heritage. Starting from the awareness that nothing can be perfectly reproduced, both in structure and texture, even more we find ourselves in the impossibility of being able to observe any artifact divorced from its concrete and real contextualization.

The highest resolution survey and the most advanced technologies can never produce the real in the sense of the twin as we would like it to be. Much less can digital reproductions be correlated with the originals of which they are a partial copy. The theoretical setting of the research thus identifies in the term *twin*, incongruence between signified and signifier; twins in fact have a usual nature, it would instead be more appropriate to speak of digital copies to already have in mind the intrinsic limitation of the action. The misunderstanding, evidently intended, may not seem foundational, but we think at the level of scientific setting it is.

To return to the question of architectural research having clarified the position, albeit in a consciously non-exhaustive way, the paper proposes a twin action of architectural study and composition. That is aimed at identifying the usual nature of the project idea starting from artifact, investigating it according to the compositional rules of architecture referring to different historical periods. Therefore, if the idea has a usual nature, we can research its premises according to the regulative logics of architectural design and here plausibly offer a digital twin of the project idea, which is then confronted with the nature of the artifact, or the cognitive process given by the physical survey and the historical documentary study. In this case then the result shifts to making the project visible from the object.

The structures that are virtually duplicated remain of the usual nature at the ontological level of idea, and the effect of this operation is an architectural image and form that mediates the direct study work on the object and the design process that preceded it. On the one hand, we are in the sphere of the late Renaissance, and we are confronted with a pragmatic architect by profession such as Antonio da Sangallo il Giovane, who in the service of the Medici family, engaged in urbanistic actions of profound transformation in that of Pitigliano, a contested episcopal city and a border town right between Rome and Florence. This area that today is called a minor interior area is characterized by castles, fortified towns and monasteries or convents, and the town of Sovana connected today with Sorano is one of these centers that supplied travertine and valuable mineral resources to Rome. The operation

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Cecilia Maria Roberta Luschi, Alessandra Vezzi, *Building's Twin Reconstruction*, pp. 1181-1192, DOI 10.36253/979-12-215-0289-3.117

carried out in Santa Maria Sovana is trying to represent an evolutionary diachronicity of a site that is resemantized within the urban grid.

2. THE DHOMUS PROJECT, MATERIALS AND METHODS

In the framework of the research described above, the DHoMus project, conducted in collaboration between the Department of Architecture (disciplinary scientific sector ICAR/17) of the University of Florence, the Diocese of Pitigliano-Sovana-Orbetello and the Diocesan Museum Palazzo Orsini in Pitigliano, began in March 2020. Action aimed at safeguarding cultural heritage and in line with the idea of a *diffuse museum* (Aiello, 2020b). Two relevant historical emergencies such as the church of the convent of St. Francesco in Pitigliano and the church of St. Maria in Sovana refer to the first museum pole in Pitigliano (Stefanini, et al. 2021).

2.1 The case study of St. Francesco church, Pitigliano

The Convent of St. Francesco, located outside the urban center of Pitigliano, is in a state of ruins today (fig. 01). In fact, the building, which was built in the XVI century to a design by Antonio da Sangallo il Giovane, was soon abandoned in the early years of the XVIII century under the pressure of the Napoleonic suppressions, leading to a gradual process of decay. In the second half of the 1900s the Diocese implemented a parceling out of the convent complex and remained the owner of only the church.

There are still many elements of interest of the ruin, in addition to its architectural definition, that lead us to focus attention on this building again.

The first phase of the study was to, as is customary, prepare an integrated survey project, which in 2019 approached a three-dimensional modeling of the actual state with care taken to keep the textural and chromatic data as faithful as possible to the actual appearance of the ruin (fig. 02) (Lecci et al. 2021). At the same time, research was carried out at the Uffizi *Gabinetto* of Drawings and Prints, a valuable fund for those interested in architectural design and the studies made by Renaissance architects.

Fortunately surviving the events of about half a millennium are two papers precisely concerning the San Francesco in Pitigliano, where the architect in the early period of his professional activity sketches two plans of the building. From some reconstructions of the activity and the placement of the drawings it is plausible to think that the church in 1522 was already definitely built.

The drawing depicts, on the recto of the page, the plan layout of the convent complex of St. Francesco, consisting of two cloisters around which the buildings are attested (fig. 03). Accompanying the project sketch is a legend indicating the function of the various buildings. What remains to this day of the entire convent is solely the church part. Church designed with a single nave with leaning against it on the long side three polygonal chapels extroflexed with internal apse. Note also that the church was planned to have a vestibule with three entrances from which to enter, now lost.

The study of Sangallo's drawing, given the differences in the church between the project and its present state, has guided the research toward a more thorough investigation of the project itself, taking an interest in how the building was conceived and how it should have looked in its original state (Aiello, 2020a).

The drawing seems to plan an overall idea and that the realization therefore according to the document could have been synchronic. The survey also provided us with a reading of the parts attributable to the original layout and thus compatible with the plan found in the Uffizi *Gabinetto* of Drawings and Prints.

The functional distribution of the architectural complex was identified directly from the legend of the original sketch. An initial graphic elaboration was carried out that could communicate this information more clearly and immediately, placing the 16th century design sketch at the center and explaining the dislocation of the rooms by highlighting them and their wording, as specified by the architect in the legend (fig. 04).

More extensive archival research identified designs that could be compared with that of St. Francesco in terms of characteristics and style, attempting to delineate the possible elevation thought up by the architect.

Fig. 1: Photo of the church of the convent of San Francesco in Pitigliano, GR.

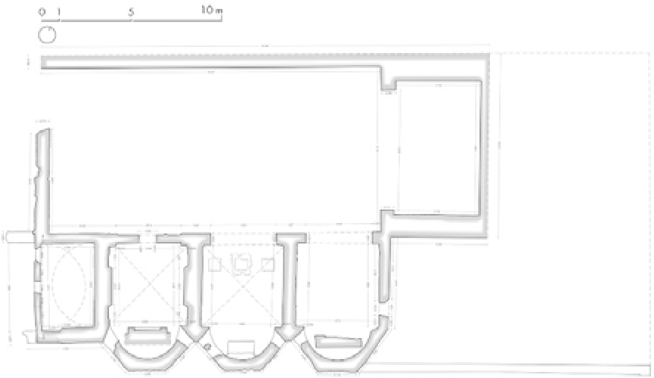

Fig. 2: Plan of the church of the convent of San Francesco in Pitigliano. Graphic elaboration obtained from the survey and developed by the arch. Luca Pasqualotti in his Architecture degree's *Abitare il Paesaggio Storico* (Pasqualotti, 2020).

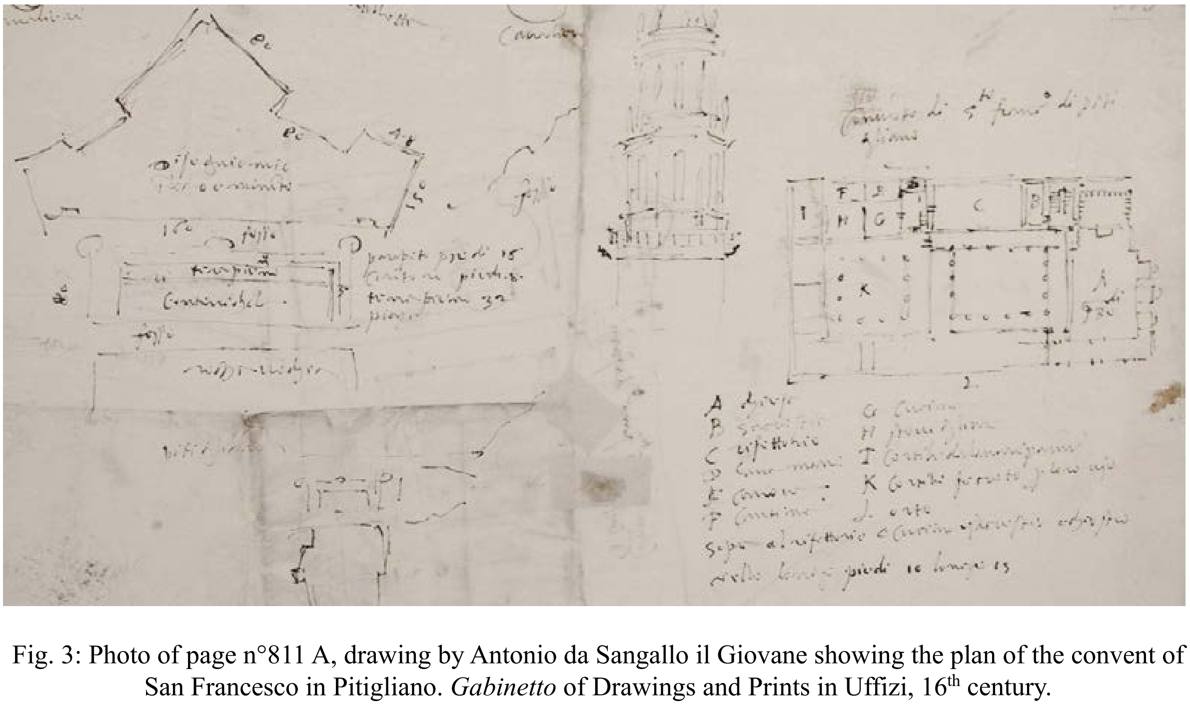

Fig. 3: Photo of page n°811 A, drawing by Antonio da Sangallo il Giovane showing the plan of the convent of San Francesco in Pitigliano. *Gabinetto* of Drawings and Prints in Uffizi, 16th century.

On the survey and the iconographic document, the metric-proportional study of the entire plan layout was carried out, with the aim of verifying whether the project, even if in the form of a sketch, had been conceived according to proportional ratios and/or according to specific mensural canons.

Such a possible positive finding would on the one hand have helped the reading of the architectural portion visible today and on the other hand would have added information about the figure of the architect himself, regarding his modus operandi as a architectural designer. The analysis was based on the planimetry, from which the design geometries were highlighted from the proportional diagrams of the two cloisters. These were then investigated for the existence of any measurement modules between them (fig. 05) (Pasqualotti, 2020). Analyzing the length and width ratios of the greater cloister revealed an internal scanning in squares of sides equal to the span of the intercolumn of the portico. This correspondence thus revealed the existence of a modularity that, aggregated in a ratio of 4:5, punctuates the entire composition of the cloister itself. The modular quantity derived from this ratio was extended to the entire plan development of the complex, bringing out the same correspondence between module and project, thus suggesting that the architect had a clear proportional geometric structure of reference (fig. 06) (Zerbini, 2022).

Fig. 4: On the left: Graphic reworking of the project sketch by Antonio da Sangallo il Giovane; on the right: visualization of the sketch showing the different functions of places.

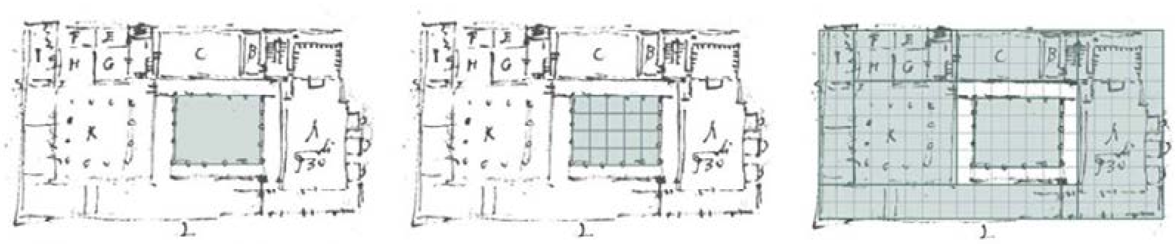

Fig. 5: Compositional-proportional studies performed on the project sketch of the plan of San Francesco's convent in Pitigliano.

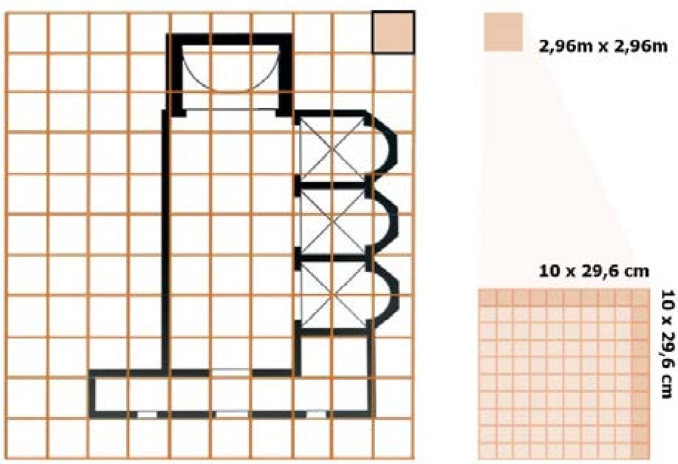

Fig. 6: Compositional-proportional study on the plan of the church through the modular grid obtained from the previous study.

The proportional geometric protocol then applied directly to the survey of the surviving structure revealed a direct match even in the elevations, which are still recognizable today. The building consistency, therefore, has been identified in its main characteristics of heights and distributions.

Missing at this point a stylistic reference to associate with the compositional one to trace the design idea. In this regard, compositional constraints of the surveyed structure were sought, such as portals, still recognizable facade openings, and traces of the ante-facade vestibule. It was then observed that the portals of access to the vestibule and the presence of a central rose window, would have conditioned the elevation of the vestibule itself, which was meant to allow direct light intake. For these reasons, the vestibule designed by Sangallo was assumed to be a single-register element, over which the gable of the church rises.

The result obtained was the subject of three-dimensional modeling, which from the plan design shows the construction of the building according to the proposed hypothesis and finally overlaps with the model inferred from the survey, of the church in its present state (fig. 07).

Two models of a different nature are thus obtained, the first is produced from a survey of the actual state, while the second is produced from a design model, constrained planimetrically and determined in elevations by the proportions introduced by the plans of the Sangallo il Giovane, and its analogous projects.

The final idea was to produce holographically, the superimposition of the two models and the representation of the document testifying to the design intention of the Sangallo il Giovane.

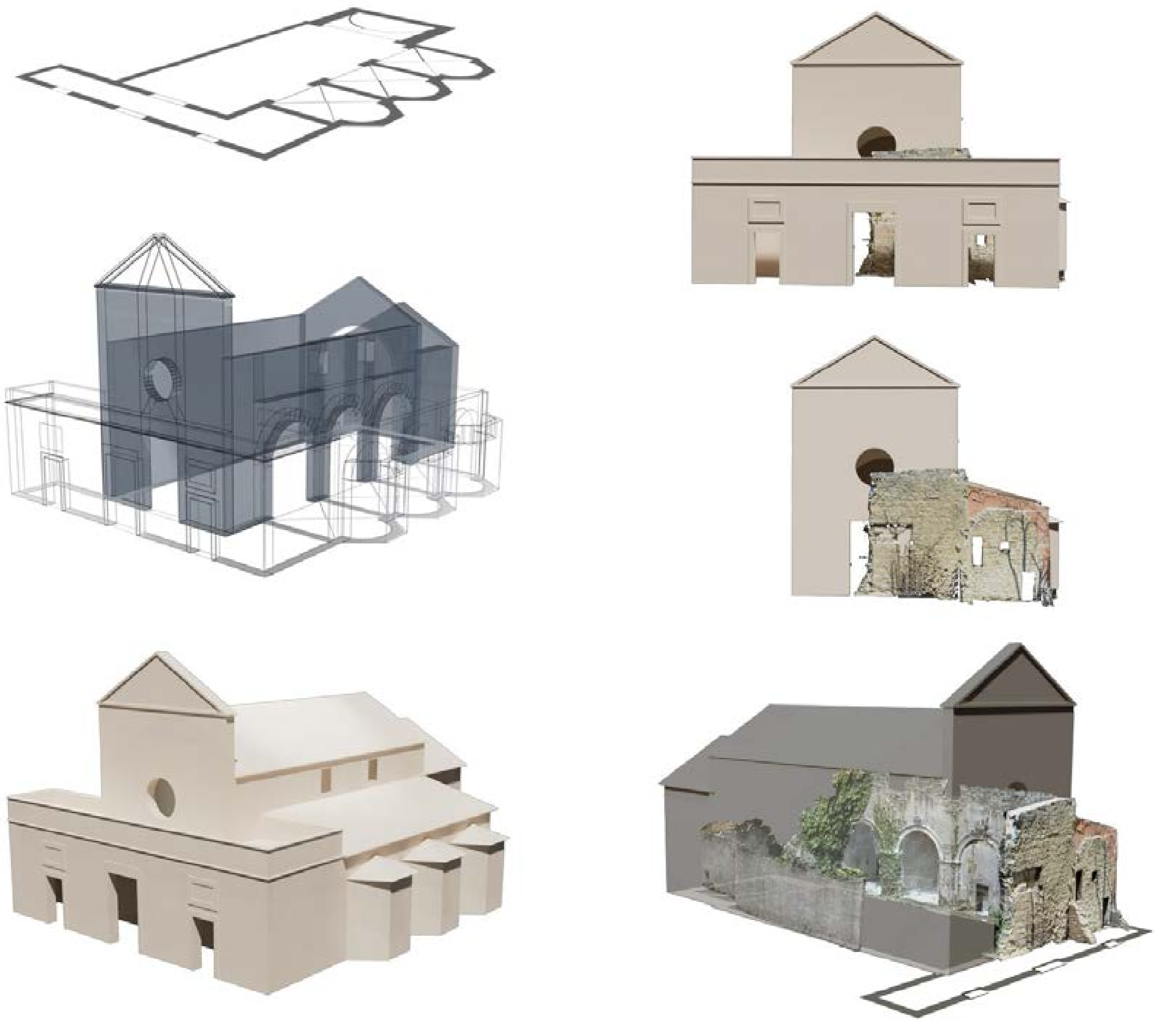

Fig. 7: Three-dimensional project of the hypothetical reconstruction of the church of San Francesco's convent according to the idea of Antonio da Sangallo il Giovane. And overlap of 3D model with the existing monument.

2.2 The case study of St. Maria church, Sovana

The small town of Sovana is characterized by the central Pretorio square and the ruins of the church of the patron saint San Mamiliano. It, believed to be the first church-cathedral of Sovana, is placed directly on the remains of an Etruscan and then Roman building almost bordering the Pretorio square whose northern edge is defined by the side of the church of Santa Maria.

It perhaps to be identified as that Santa Maria, which is consecrated by Bishop Ranieri of Tuscania in 1208, is certainly mentioned already in the will of Count Ildebrandino Aldobrandeschi, called *il Rosso*, of 1284, and recorded in the Decimari of 1296. In 1321-24, it was looted and possibly damaged by the Sienese in 1410 and by the people of Pitigliano in 1434. Around 1558, the construction, on the initiative of Grand Duke Cosimo I de'Medici, of the Loggia with archive building, later to become Palazzo Burbon del Monte, deprived it of its facade, limiting access to only the side portal, open to the square (fig. 08).

The interior of the church is of the basilica type, with three naves divided by polygonal pillars supporting wide round arches. The nave is divided into three bays by Gothic transverse arches, on which the wooden trusses of the roof are set. In the center of the presbytery, raised on a few steps, is the famous ciborium (VIII-IX century), the only example of its type in Tuscany, referable to the pre-Romanesque period (fig. 09) (Rivetti, 2018).

In the work being presented, it is interesting to consider the urbanistic placement of the church in relation to the whole plan the plant. The latter consists of the square and a series of water distribution infrastructures that affect the last terracing where the entire city is set. The church, therefore, is in line with the oldest route that leads directly to the site of the present cathedral. Along this route, in the proximity of the apse of St. Maria's itself is the Public Fountain, currently facing the square, and a wash house at a lower level than the Fountain, adjacent, however, to the extroversion of the church's apse. In further analyzing the archival documents in the Technical Report of the Superintendence for the consolidation works of the church in 1984 it appears that in the apse outside during the excavation an empty archway was found, probably a possible ancient water access route connected to the water system described above (fig. 10).

The continuing problems inherent in rising damp that affected the interior of the church induced to investigate what kind of water structure was present of the area at the time before the church was built. In 2021, thanks to the INGV (National Institute of Geophysics and Volcanology) of the CNR in Florence, it was possible to resort to a geophysical exploration inside and outside the church by means of an electromagnetic radar technique (Ground Penetrating Radar, GPR) survey at 300 MHz and 800 MHz. This made it possible to investigate the stratigraphic conformation and the presence of any structures in the subsurface. The results obtained indicate that there is a depressed area under the church with a compluvial development at the bottom, probably backfilled with material similar (tuffaceous elements) to that of church construction. The compluvium appears to be directly in axis with the apse and its opening to the outside described above, still present today, and a collector placed in the direction of the present wash houses (fig. 11).

The water line, therefore, running from the cathedral to the main square, suggested the possibility that it was a permanence of water system of the classical period, also given the baths of the villa under San Mamiliano. The geophysical survey, moreover, returned a different density of material between the area of the aisles and the central nave of the church opposite the apse, delineating a well-defined rectangular area that ends in conjunction with the two rows of pillars. Opposite the present chancel, a very large apsidal form can be discerned that opens and extends the entire length of the church. This materializes a kind of double-apsidal plan with a central basin and an inflow channel that were placed in axis with the entire external water system (fig. 12).

Regarding the problem of continuous rising damp that still affects the structure today, it is shown that water continues to pass through by capillarity. It is noted how the level of humidity is distributed on the floor forming a hemicycle opposite to that of the apsidal basin of the church. These results gave the possibility to advance hypotheses about the previous use of the area by focusing on possible references to nymphaea of urban areas of Roman cities or classical in general, tried to connect the various outcrops of water adduction.

To make visible all that the instrumentation identified and highlighted, the choice was made not to make a copy of the church itself as such, but to structure a possible evolution from the Classical hypogeum layout to a conversion of the structure into a religious site of the early medieval period. The choice of 3D reconstruction is emphasized by the choice of the use of holographic representation, which through moving scenes, comprehensively depicts the steps in the history of the city of Sovana (Stefanini, et al. 2022).

Fig. 8: Photo of the church of S. Maria in Sovana, GR.

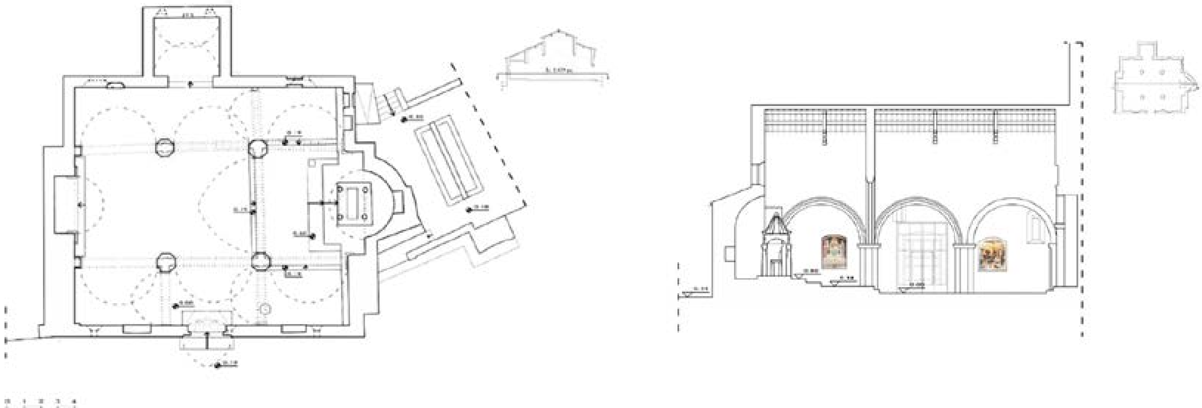

Fig. 9: Graphic elaboration obtained from the survey and developed by the arch. Domenico Rivetti in his Architecture degree's *Il battistero di S. Maria nella profondità della sua storia*, 2018.

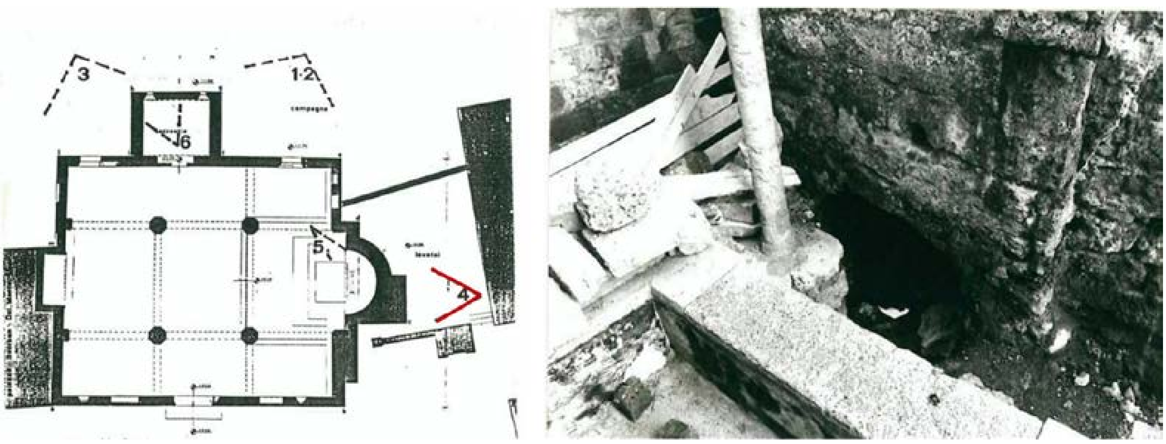

Fig. 10: Technical Report of the Superintendence, 1984. Detail of the empty archway found in the apse outside during the excavation.

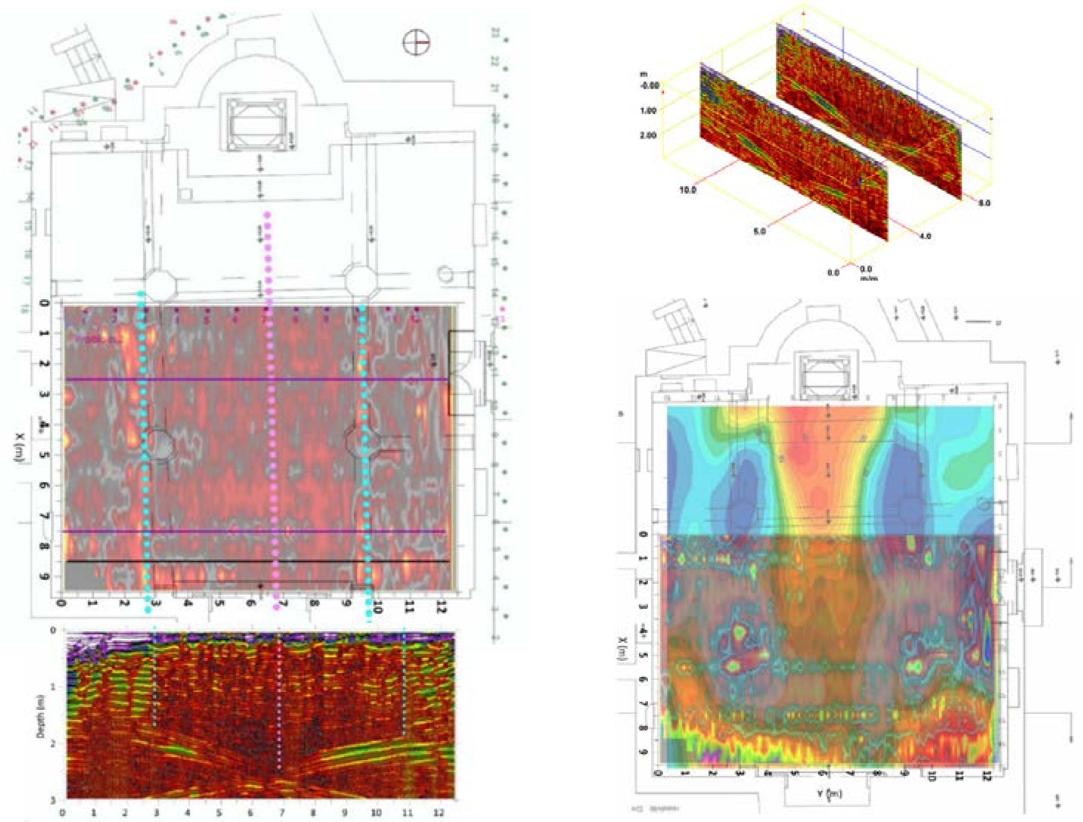

Fig. 11: Geophysical survey, 2021. INGV of CNR of Florence. On the left: internal section of the church GPR 300 MHz (z=190cm) - Line 8.5m. On the right: overlay of EMP 400 and GPR 800 MHz comparative analysis.

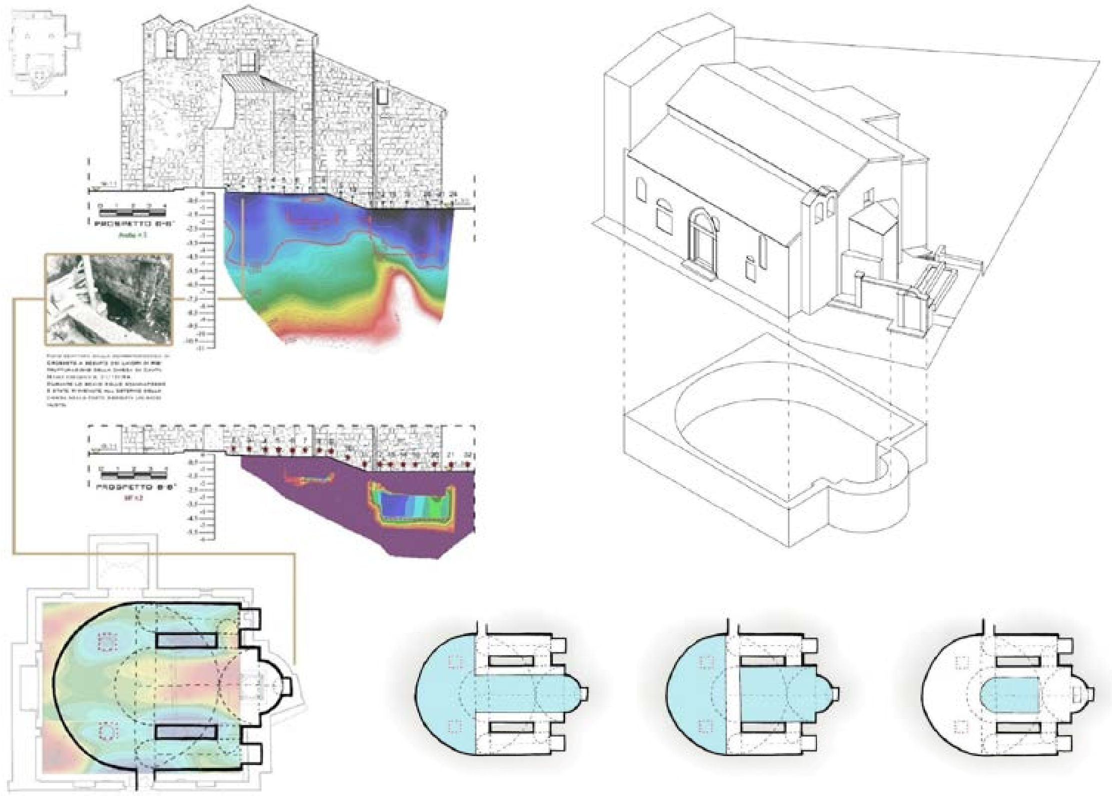

Fig. 12: Reconstructive hypothesis of nymphaeum types present in the hypogeum of the church of St. Maria. Arch. Domenico Rivetti in his Architecture degree's, 2018.

3. RESULTS

Operationally, the holographic representation, is actualized through the support of the holographic showcase, an instrument formed by a monitor that contains the images or video to be projected. They are reflected on the glass faces of a hollow pyramid trunk and recomposed in the center. The operation is based on the theoretical principle of projective geometry, whereby the image, or video, contained in the monitor is projected onto the transparent surfaces inclined at 45° of the prism, directly applying the principles of projectivity (homology) (Lecci, et al. 2019).

Interestingly, at a strictly operational and technical stage, a properly theoretical principle is being materialized into a result provided by theory. The principles of projective geometry make it possible to faithfully recreate an image or video animation of digitally made objects that appear via optical effect, in a three-dimensional view at the center of the pyramid (Yamanouchi, et al. 2016). To create the holographic projection, it was necessary to make a video that would show all the stages of the research previously described and be able to communicate the story of the building clearly and directly. The work involved writing a storyboard of the research contents and making them the protagonists of the images to be produced, structuring a storytelling to be included in the holographic showcase. To do this, the 2D and 3D material obtained from the survey was used, with which a real narrative plot was developed for the creation of the video animation (Gabellone, 2014).

The storyboard made it possible to sequence all the steps to be told, hierarchizing the information and, at the same time, managing its timing, effects, and steps. In the case of the church of St. Francesco, the paper document becomes the protagonist of a three-dimensional reconstruction of the project that then gradually reifies into the remaining structure of that architectural idea of which we have the trace sketched as a starting point. Geometric analysis of the plan follows until the building is made visible according to the architect's compositional ideas, finally arriving of what remains of the walls of the present ruin (fig. 13).

In the case of the church of St. Maria, on the other hand, the narrative starts from the dissolving of the interior and exterior walls of the church until it arrives at the level of the floor, beyond which the reconstructive hypothesis of that hypogeous environment, known only through the studies carried out on the subsoil, is depicted. Thus, what is not visible is made visible, leaving an idea, a curiosity about what is hidden under the thick walls of the Sovana church that we still see today (fig.14).

3.1 The choice of hologram projection

Using high technology and new methods of digital representation such as holography, we expect to develop more explanatory and engaging narratives (Luschi, et al. 2023). Holograms become a form of interactive and educational visualization, closer to reality by distancing themselves from the use of the support of visors (VR) that isolate from the outside world.

With the implementation of the above-described videos in the holographic showcases inside the Diocesan Museum of Palazzo Orsini in Pitigliano, it was possible to give visibility to the museum and its inaccessible external archaeological sites, making them virtually visitable (figs.15,16).

The museum reality has the purpose of both musealization and being able to have effective communication with visitors. The goal is to present new forms of communication that allow the dissemination of knowledge about the historical-archaeological heritage. Allowing the involvement of increasingly diverse user targets, offering a complete and satisfying visit (Lecci, et al. 2022).

4. CONCLUSIONS

The results that have emerged from the two approaches and experiences are of different tenors. The first that of the church of St. Francesco is the attempt to pursue an idea that leaves its trace from the beginning for the conception of the drawing, to its realization. In between these two major terms is an activity of logical reconstitutions of the project idea that is verified in parallel, both by the drawing and the preliminary sketch, and by the result whereby the extreme terms make the intermediate procedure more and more plausible.

The second experience, on the other hand, there is an evolution to be made visible, still, and partly inaccessible. The technology used puts us in a position to extrapolate a drawing. This drawing is a fact that, however, must be compared with the actual drawing of the church of St. Maria.

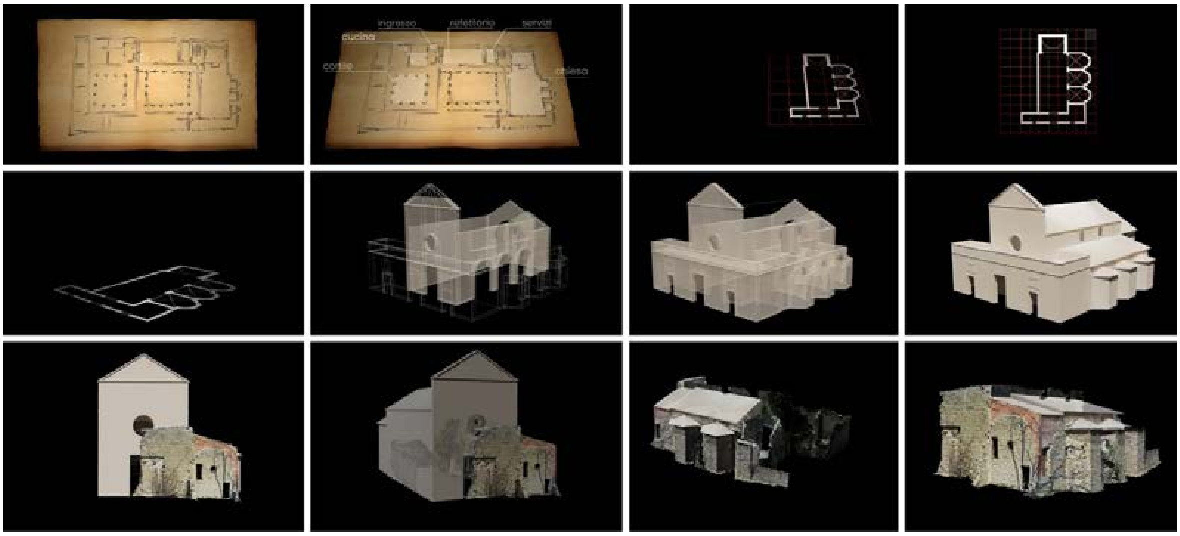

Fig. 13: Some frames in sequence of the video elaboration of St. Francesco's convent in Pitigliano, created to be projected inside the holographic showcase.

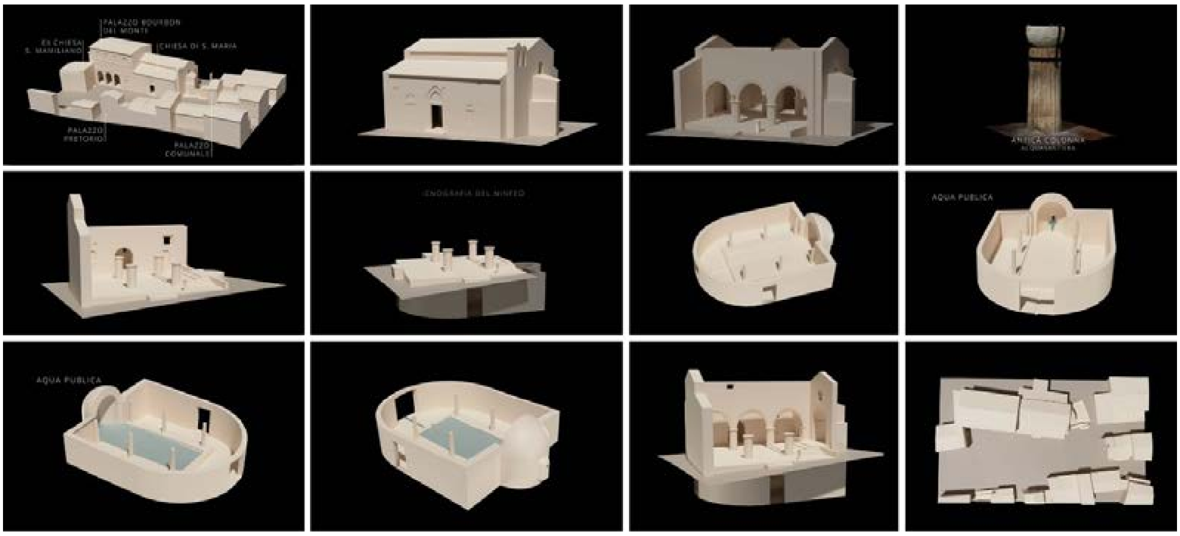

Fig. 14: Some frames in sequence of the video elaboration of St. Maria in Sovana, created to be projected inside the holographic showcase.

Fig. 15: The showcase shows the holographic projection of the video, as indicated by the sequence of frames.

Here it is that between these two moments a logic must intervene introduced precisely by a digital model that mediates the positions, the hypotheses and makes them visible in a becoming understandable and consistent with what are the scientific data placed at the end of it.

So, if in the first case there is a drawing of a project and then a verification of that data through a model, in the second case we have two survey models of a different nature working together and helping to verify the evolutionary stages of a site. Focusing not on the representation of the object itself but of an evolution of an idea and a resemantization of urban spaces.

The digital copies, then, managed to show the effectiveness of a research and its different moments of in-depth reconstruction of hypotheses, returning a unicum that is coherent and somehow re-presenting the becoming of these architectures, in the passage of time.

Fig. 16: Photos of the holographic showcases with their projections, inside the Museo Diocesano of Palazzo Orsini in Pitigliano, on the inauguration day, year 2021.

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A SEMANTIC DIGITAL TWIN PROTOTYPE FOR WORKPLACE PERFORMANCE ASSESSMENT

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ABSTRACT: *Nowadays, despite the growing attention to indoor environmental quality and comfort, existing workplaces still often fail to meet employees' expectations and needs, affecting their well-being and productivity. In order to improve management decisions, crucial insights can be provided by the timely correlation of objective workplace conditions, observed by sensors, and subjective workers' feedback, collected through Ecological Momentary Assessment (EMA) method. This paper presents a prototypical Digital Twin for the assessment of workplace performance from an occupant-centric perspective, based on the integration of IoT, BIM and Semantic Web technologies. Following the definition of relevant use cases and requirements a layered system architecture is presented and the prototype implementation is discussed. For capturing the workplace's environmental properties, a sensor network based on the Zigbee communication standard is proposed due to its data transmission efficiency. The measured data, converted in the lightweight MQTT protocol, are streamed to an InfluxDB time series database where they are stored along with the incoming workers' feedback collected as survey responses with a dedicated web application. These time series data are queried and transported into a developed web platform for integrating BIM and RDF data within the standardized structure of Information Containers for linked Document Delivery (ICDDs). Inside this platform, the IFC model of the workplace, the measured data from the sensors, and the worker generated RDF data according to the WOMO ontology for occupant-centric workplace management are linked. The capabilities of the workplace Digital Twin prototype are finally demonstrated querying the linked heterogeneous data to fulfil workplace management tasks in a case study provided at the end of the paper.*

KEYWORDS: *Digital Twin, Workplace performance assessment, Well-being and productivity, Linked Data, Information Container for linked Document Delivery (ICDD), Semantic Web, Internet-of-Things (IoT).*

1. INTRODUCTION

Providing high-quality indoor workplaces that meet their occupants' needs is a challenge of utmost importance for Facility Managers (FM) because of the critical impact they have not only on employees' quality-of-life, health and well-being (Vischer and Wifi, 2017), but also productivity (Al Horr, Arif, Kaushik, *et al.*, 2016). However, although the growing adoption of Information and Communication Technologies (ICT) to control and automate building systems (e.g. HVAC, lighting, access, etc.) has enabled an unprecedented granularity and interactivity in the operation of workplaces, evidence suggest that they still fall short of their occupants' expectations (Abbaszadeh *et al.*, 2006). To address this issue, occupant-centric approaches for control and operation of buildings have been recently proposed, shifting the technology-centred paradigm to the recognition of the user, with its individual and dynamic physiological and psychological requirements, as the most critical component in the occupant-building system (O'Brien *et al.*, 2020).

Recent research focused on supporting managers in the assessment of workplace performance providing them a constant holistic understanding of employees' individual activities, preferences, and conditions within their physical and social work environment. In this regard, effective solutions have been proposed for the timely

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Alessandro Bruttini, Philipp Hagedorn, Felix Cleve, Vito Getuli, Pietro Capone, Markus König, *A Semantic Digital Twin Prototype for Workplace Performance Assessment*, pp. 1193-1205, DOI 10.36253/979-12-215-0289-3.118

collection of occupant- and building-generated data and their semantic integration, processing, and visualization using Building Information Modeling (BIM), sensor networks and Semantic Web technologies (Abdelrahman, Chong and Miller, 2022; Donkers, de Vries and Yang, 2022a). However, the development and implementation of these approaches for workplace management purposes are still in their early stages due to limitations in domain knowledge representation, and heterogeneous data integration strategies that need further investigation.

In order to address these issues, this paper presents the concept of a semantic Digital Twin for the integration and exploitation of heterogeneous workplace data, built on the findings of previous contributions by the authors. The research framework and workplace domain knowledge formalization are discussed in Bruttini *et al*., (2022), while the storage and processing of semantic data pivots on the use of standardized information containers (ISO 21597-1:2020) through a dedicated web platform whose effectiveness has been demonstrated in asset and project management use cases (Sigalov *et al.*, 2021; Hagedorn, Liu, *et al.*, 2023). In the followings, after the discussion of the findings of relevant related works, the system development, prototypical implementation and case study demonstration for a workplace performance use case are provided.

2. BACKGROUND

Over the past decade, the pursuit of the benefits obtainable with data-driven management and control of the built environment with the specialization of the concept of “Digital Twin” for the AECO sector, has witnessed an exponential growth (Sacks *et al.*, 2020). The use of Sematic Web technologies and the diffusion of the Linked Building Data (LBD)[1] approach paved the way for the integration of heterogeneous information from diverse knowledge domains, hence overcoming the initial limitations of BIM. In particular, the possibility to observe building operational conditions, e.g., indoor environmental quality (IEQ) factors and systems status, and contextually evaluate them against the way the occupants behave and perceive a given space, enabled an unprecedented understanding of building-occupant complex interactions, starting the long-awaited paradigm shift towards occupant-centric approaches in building management and operation (O’Brien *et al.*, 2020).

In the following paragraphs, the findings and limitations of recent relevant studies related to occupant-centric building operation and workplace performance assessment are reported. Then, a review on sensor network solutions for building monitoring is presented and the state-of-the-art for the semantic integration of building data is discussed.

2.1. Occupant-centric building operation and workplace performance assessment

An indoor workplace represents a complex system characterized by dynamic mutual interactions between the physical space and its occupants. Therefore, to assess workplace performance, quantifying the extent to which it supports workers’ activities and meets their needs and expectations is crucial. In this regard, extensive literature investigated the impact of different physical and non-physical factors on workers’ satisfaction, productivity, and well-being, from workplace IEQ parameters (Al Horr, Arif, Katafygiotou, *et al.*, 2016) to workspace layout (Kim and de Dear, 2013) and the degree of user perceived control on the environment (Luo *et al.*, 2016).

To monitor how these and other heterogeneous factors affect the workers, both building objective properties, observed by sensors, and workers subjective conditions must be timely collected and integrated. For the latter, indirect approaches based on inferences from historical building systems’ data (e.g., lighting usage for visual quality assessment) are making way to the collection of direct occupant feedback through smartphone and web applications and wearable devices (Nagy *et al.*, 2023). For this purpose, the Ecological Momentary Assessment (EMA) approach (Shiffman, Stone and Hufford, 2008) initially developed for medical and social researches, is progressively replacing Post Occupancy Evaluation (POE) for the collection of frequent, real-time occupants’ feedback directly from their workplace environments via the use of micro-surveys (Engelen and Held, 2019).

Nonetheless, a system that enables the semantic integration, processing, querying and visualization of building- and worker-generated data is necessary to support occupant-centric workplace management and performance assessment. In this regard, recent contributions showed the feasibility and opportunities provided by the adoption of BIM, sensor networks and semantic web technologies for the integration of static and dynamic domain-

[1] W3C Linked Building Data (LBD) Community Group - https://www.w3.org/community/lbd/ - (accessed 12/07/2023)

specific data for IEQ and occupant experience assessment (Abdelrahman, Chong and Miller, 2022; Donkers, de Vries and Yang, 2022b, 2022a). However, since indoor workplace management purposes still need to be fully addressed with specific solutions, the authors developed a framework and an ontological representation of worker's conditions and activities in indoor environments which form the conceptual basis of the workplace digital twin prototype proposed in this paper (Bruttini *et al.*, 2022).

2.2. Sensor networks for building monitoring

For the contextualization of subjective worker's data, his surrounding environmental conditions must be objectively observed through a sensor infrastructure which provides for sampling, transferring, and storing of the sensed data. In recent years, Internet-of-Things (IoT) technology has established as the main solution for the implementation of such sensor networks. Most of them make use of a similar multi-level hardware architecture that addresses the above-mentioned challenges. Kifouche *et al.* (2017) describes three levels, the sensor-, gateway- and base-station-level. Li *et al.* (2023) add a further application-layer for data visualization interfaces.

Concerning the sensors, both wired and wireless solution can be deployed. While the former can be more reliable, it needs additional cabling and therefore lacks in flexibility (Tanasiev *et al.*, 2021). Hence most of the studies use wireless solutions, relying on sensor devices that consist of a sensing unit, a microcontroller and a radio adapter for the data transmission. As sensing unit, anything from the widely used temperature and humidity sensors up to a motion or CO_2-level sensor is possible. A microcontroller reads out its data and sends them to a gateway via Wi-Fi, Bluetooth (Li *et al.*, 2023), Zigbee (Kifouche *et al.*, 2017) or LoRa (Kifouche *et al.*, 2017; Tanasiev *et al.*, 2021). As wireless sensors are mostly battery powered, power management is a crucial aspect, finding the right balance between power consumption, bandwidth, and transmission range. While some studies assemble their own sensor devices on a prototypical base, there are approaches as well that make use of out of the shelf sensor devices with proper device housing (Chamari, Petrova and Pauwels, 2023).

The gateway is placed on site and acts as a translator receiving data from the sensors and routing them into the backend system. Thus, the selection of the radio technology and communication protocol, together with the building substance and materials, substantially effects the network range, determining the number of gateways needed for a seamless coverage inside the building (Kifouche *et al.*, 2017). As used within several works (Kifouche *et al.*, 2017; Tanasiev *et al.*, 2021; Li *et al.*, 2023), it is suitable to implement the gateway with a low cost SoC computer like a Raspberry Pi, which connects via Ethernet with the backend system.

Detached from the installation on site, the backend system can be deployed anywhere else, even in the cloud. It implements a software solution for processing and storing the forwarded data. While earlier works made use of individually designed solutions (Kifouche *et al.*, 2017), recent studies showed the effective adoption of the machine-to-machine (M2M) and IoT protocol called Message Queuing Telemetry Transport (MQTT) (Tanasiev *et al.*, 2021; Chamari, Petrova and Pauwels, 2023; Li *et al.*, 2023). Eventually, besides relational databases such as MySQL(Kifouche *et al.*, 2017; Tanasiev *et al.*, 2021; Zhang and Beetz, 2022; Li *et al.*, 2023), for storing sensor observations the adoption of NoSQL, time series databases and RDF data stores is growing especially in semantic information model applications (Chamari, Petrova and Pauwels, 2023).

2.3. Linked Data and information containers for semantic Digital Twins

With the recent advent of the Digital Twin paradigm in the AECO sector, viable solutions for the integration of BIM with both static and dynamic data for the real-time representation of physical built assets became crucial. In this regard, several studies proved that the adoption of Semantic Web technologies and Linked Data approach enable the deployment of semantic Digital Twins where building information can be enriched via linking with heterogeneous domain-specific data, whose representation is in turn demanded to dedicated ontologies (Mavrokapnidis *et al.*, 2021; Eneyew, Capretz and Bitsuamlak, 2022).

However, in a context where a standardized approach for the creation and maintenance of Digital Twins is still missing and systems' requirements are subject to frequent transformation, using BIM data and models as common basis for the implementation of domain-specific Digital Twins with a modular approach can provide the much-needed flexibility and scalability. Kosse *et al.*, (2023) argue how modular Digital Twins can be implemented with the use of standardized information containers which provide a model for storing and exchanging heterogeneous information. In particular, as shown in Polter and Scherer (2023), and Zinke *et al.* (2023), Information Containers for linked Document Delivery (ICDDs), compliant with the ISO 21597-1 (2020), are suitable for this purpose since they implement a vendor-neutral data structure which integrates, besides payload documents to be exchanged, distributed linked data. Moreover, supporting the Linked Data approach, their interconnection to web standards such as HTTP and REST is easily implementable, while Semantic Web technologies enable data retrieval through SPARQL queries. Arbitrary data can be modeled using an ontological layer that can be stored in the container or as web resources, while a specific linking structure supplements the capability of the container to host a Digital Twin. Furthermore, as demonstrated Senthilvel and Beetz (2021), the possibility to nest and interlink ICDD individual container modules opens to a scalable system-of-systems approach where compatibility is ensured by the containers' conformity to ISO 21597.

Likewise, in previous research the authors showed the feasibility and versatility obtainable with the adoption of ICDD containers for the storage, integration, querying and visualization of building and domain-specific information with the development of a dedicated web platform. With differences in implemented functions and user interface, the proposed approach proved effective for different use cases, including infrastructure asset management (Hagedorn, Liu, *et al.*, 2023), and smart contracts-based automated payment and contract management (Sigalov *et al.*, 2021). On this basis, as detailed in the followings, a customized version of the mentioned ICDD platform is proposed for the implementation of the presented workplace digital twin prototype.

3. RESEARCH FRAMEWORK AND METHODOLOGY

The present study is part of a broader research effort which aims at the realization of a data-driven workplace management framework finalized to the enhancement of workers' well-being and productivity through capturing and understanding the dynamic worker-workplace interactions. To achieve this goal, a workplace semantic digital twin, able to integrate heterogeneous occupant- and building-generated data for workplace management purposes, is proposed. With reference to Fig. *1*, this paragraph describes the study's methodology, from the system conceptualization to its prototypical implementation to a room-scale case study.

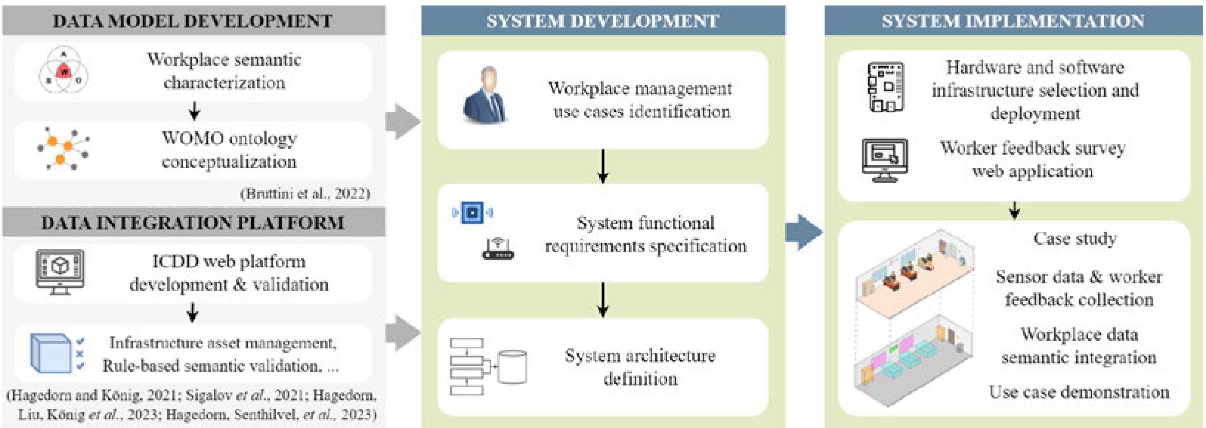

Fig. 1 Research methodology

As discussed above (see §2), the development and implementation of the proposed system stems from previous authors' contributions. The formal representation of workplace knowledge, characterized as the intersection of the worker-building-activity semantic domains, is provided in the Occupant-centric Workplace Management Ontology (WOMO) presented in Bruttini *et al.*, (2022). Workers' objective and subjective features, along with their current activity, are described and interlinked through feedback instances, hence related to the correspondent building spaces and conditions. These are represented by reusing well-established ontologies, such as the Building Topology Ontology (BOT)[2] and Semantic Sensor Network ontology (SSN)[3]. In turn, for the semantic storage and integration of the aforementioned heterogeneous workplace data, standardized information containers (ISO 21597-1, 2020) are adopted. Therefore, the workplace knowledge base, comprising of its IFC model, workers' and sensors' data, is realized through an ICDD container and semantic data integration,

[2] https://w3c-lbd-cg.github.io/bot/ - (accessed 12/07/2023)

[3] https://www.w3.org/TR/vocab-ssn/ - (accessed 12/07/2023)

querying, visualization, and rule-based validation are enabled by a dedicated web platform developed by the authors (Hagedorn, Pauwels, *et al.*, 2023; Sigalov *et al.*, 2021; Hagedorn, Liu, *et al.*, 2023; Hagedorn, Senthilvel, *et al.*, 2023).

The system development involved three main steps, namely: use cases' identification, requirements definition and architecture conceptualization. Then, the criteria for the selection of the hardware and software solutions for the system prototype implementation are described, including the development of a custom web application for the collection of workers' feedback. Eventually, the capabilities of the prototype are evaluated for a case study office room. A workplace performance assessment use case is tested through the querying and visualization of the collected workers' feedback and contextual observed environmental conditions.

4. SYSTEM DEVELOPMENT

4.1. System use cases

According to the research framework's overarching goal and to the scope and purposes that drove the workplace domain knowledge formalization within the WOMO ontology (Bruttini *et al.*, 2022), the system shall inform and support managers' decisions for the improvement of employees' well-being and productivity, providing insights from the correlation between workers' subjective feedback and workplaces' objective conditions. For this purpose, three general use cases have been identified, namely:

- *Workplace performance assessment* – Evaluation of how a workplace supports or hinders its occupants through the correlation of workers' subjective feedback with the objective indoor environmental conditions.
- *Workplace issue discovery* – Evaluation of the factors that contribute to the occurrence of unsatisfactory conditions and identification of latent issues that affect workers' needs (e.g., privacy, focus, lighting, etc.).
- *Worker preference clustering & Spatial recommendation*: Recognition and evaluation of recurrent data patterns and correlations, and implementation of artificial intelligence-enabled methods for learning and predicting ideal conditions for worker groups or profiles (e.g., based on environmental preferences, activity needs, etc.), and for the recommending solutions for underperforming spaces or occurred issues.

The presented system prototype implementation focuses on the *workplace performance assessment* use case, leaving the remaining to future developments.

4.2. System requirements

The system requirements, on which the following system architecture conceptualization and prototype implementation is based, are listed below per functional area:

- *Building-generated data collection* – To monitor workplace's indoor environments, the sensors' typology and communication protocol shall favour easy, flexible, and affordable deployment while providing reasonable accuracy.
- *Occupant-generated data collection* – The collection of worker objective and subjective data shall be using voluntary feedback responses to timely micro-surveys developed according to the EMA methodology. Feedback time and location are mandatory, while customizable feedback request's generation (e.g., scheduled, voluntary), survey's prompts and rating scales shall be granted. Collection of workers' momentary health indicators (e.g., heart rate), environmental preferences (e.g., thermal quality), and self-assessed conditions (e.g., productivity) shall be enabled along with their current activity.
- *Time series data handling and storage*: Both the transmitted building- and occupant-generated data shall be stored and organized in a store specialized for time series data. The database structure shall not be constrained in terms of data sources (i.e., sensors, feedback interfaces) and structure (i.e., building observed properties, worker data and survey fields), and shall allow data storage efficiency (i.e., down sampling), querying and aggregation.
- *Data semantic integration, querying and visualization*: Heterogeneous static and dynamic workplace data shall be integrable to realize an evolving workplace knowledge base where information is semantically structured and interlinked according to acknowledged ontologies, and reasoning, querying, and visualization are enabled. This shall include, but not be limited to, the geometries and properties of building spaces and elements (i.e., IFC model), sensors' observations and workers' feedback.

4.3. System architecture

On these assumptions, a comprehensive four-layered system architecture has been drawn as shown in Fig. *2*. At the bottom, the *physical layer* represents the physical workplace from which the data describing the building operational and environmental properties (e.g., air temperature, window opening, etc.) are collected by the deployed sensors, and workers' objective and subjective data (e.g., location, environmental preference, activity, etc.) are provided via momentary feedback. This layer transfers the data to the upper *data storage layer* where two functionally distinct stores are identified: one dedicated to dynamic data (i.e., timeseries sensors' observations and workers' feedback); the other, dedicated to consolidated data (e.g., aggregated sensor observations) and less frequently changing or static building information. The latter forms the system's core knowledge base, where workplace heterogeneous information (e.g., BIM model, organizational data, timeseries, etc.) are stored according to appointed ontologies and hence semantically interlinked.

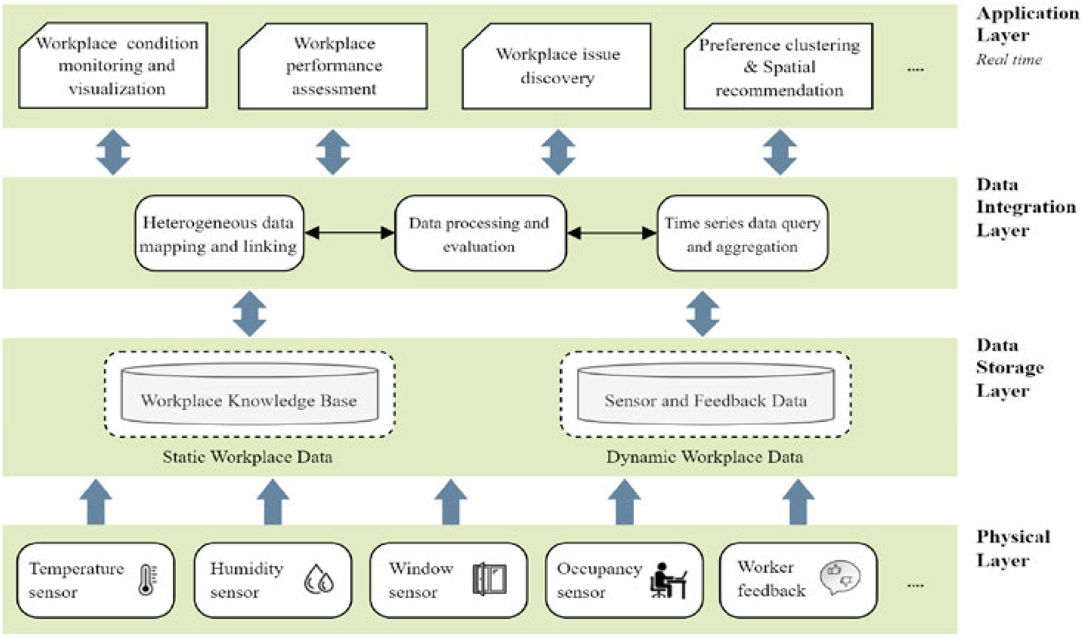

Fig. 2 Workplace digital twin system architecture

In turn, the *data integration layer* provides access to the workplace static and dynamic data, allows for their semantic integration and processing, and mediates the incoming requests from the top *application layer*. This last layer provides the user, i.e., manager, with the digital twin-based services that shall serve the identified use cases, such as: workplace condition monitoring and visualization; building-activity-worker data correlation for workplace performance assessment, issue discovery and spatial recommendation.

4.4. System prototype implementation

This paragraph describes the hardware and software choices taken for the system prototype implementation. As shown in Fig. *3*, the physical workplace can be represented as the combination of several workspaces (i.e., building's spaces) that shares spatial, organizational, or functional properties at different scales and are occupied by the workers during their daily working routines (e.g., a part of an open space, a single room, a workstation, etc). For this implementation, the system's targeted workspaces consist in private or shared office rooms with a gross floor area not exceeding 50 m^2. For workspace properties monitoring, a wireless network based on the Zigbee communication standard has been chosen due to the acknowledged performances in terms of network reliability, ease of deployment and affordability of compatible commercial devices in smart building applications. Three types of sensors have been selected to monitor objective workspace properties, namely: temperature and humidity sensor for the thermal environment; contact sensor for window status; motion sensor for occupancy detection and count. All types of sensors are battery-powered, can be installed without screws and transmit data wireless, allowing for fast and flexible deployment, substitution, and maintenance. A Raspberry Pi[4]

[4] https://www.raspberrypi.com/products/raspberry-pi-3-model-b/ - (accessed 14/07/2023)

SoC provided with a universal USB Zigbee gateway is appointed as network coordinator and transmits sensor data to the system backend via Ethernet connection. Moreover, the mesh topology of the Zigbee network allows for the addition of power-supplied devices acting as repeaters (e.g., smart plugs), hence providing redundancy and easy range extensibility.

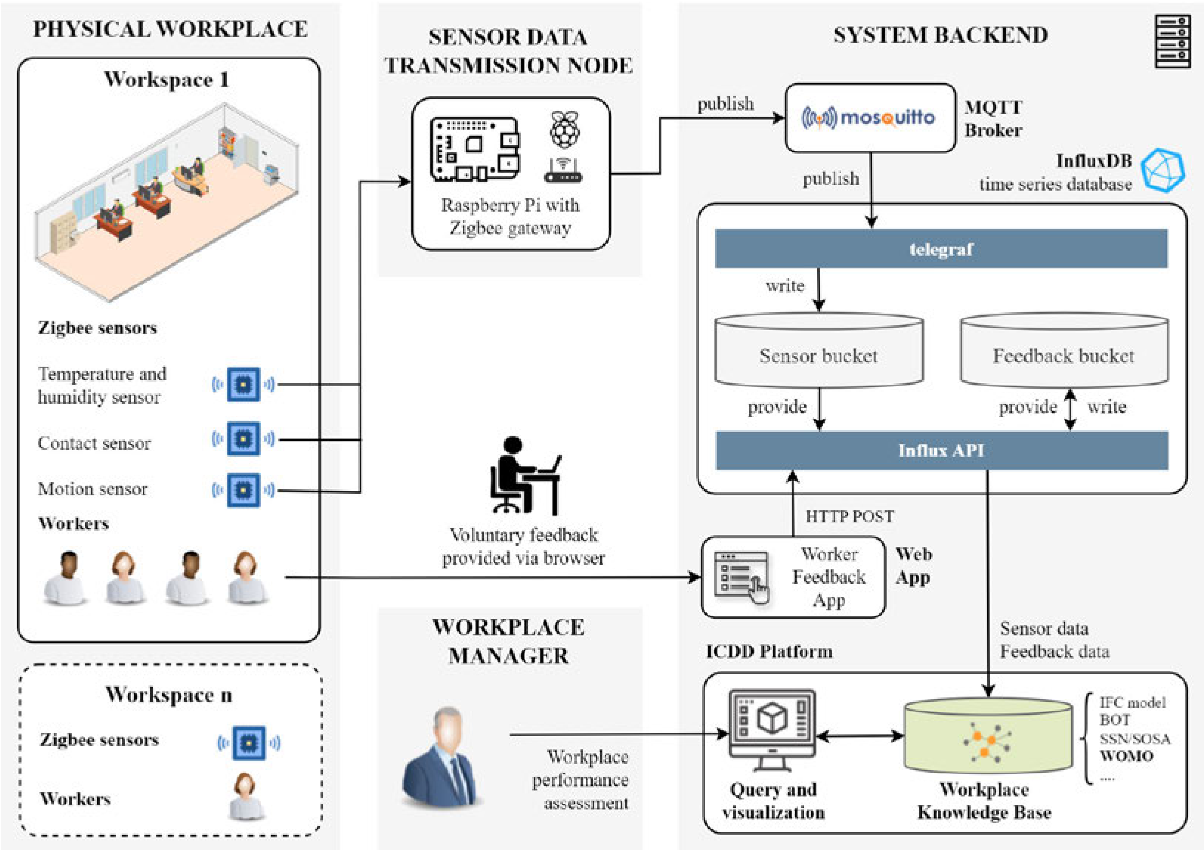

Fig. 3 Workplace digital twin system prototype implementation scheme

The encoding and transmission of the sensors' data has been demanded to the MQTT protocol due to its suitability in IoT applications that requires lightweight, machine to machine, message exchange. The sensors' observations (i.e., actual measurements and metadata) are gathered from the gateway, encoded into individual message packages, and published via MQTT protocol on dedicated topics, one for each sensor, to an Eclipse Mosquitto[5] broker instantiated at the system backend. On the same server, an InfluxDB[6] timeseries database instance connected with an agent (i.e., telegraf [6]) to the MQTT broker and subscribed to all relevant topics receives and stores the sensor-generated data into a dedicated bucket.

For the collection of workers' data, a web application presenting a one-page survey form has been developed. Accessing the form via browser, workers can provide feedback instances on a voluntary base. The survey interface is designed to allow fast responses in order to prevent survey fatigue bias. For this reason, worker ID and current location, corresponding to their allocated workstation, are preset and not editable by the responder. The other survey fields allow for multiple choice response and can be customized to query for the current worker activity and to express their environmental preferences and self-assed conditions. The survey web application uses the HTTP POST method and the Influx API to transmit and write the collected responses to timeseries records within a dedicated feedback bucket in the InfluxDB database.

The last component of the prototype implementation consists in the aforementioned web platform through which the heterogeneous workplace data are stored in a dedicated ICDD container, are semantically interlinked according to predefined ontologies and hence processed, queried, visualized. Here, the workplace IFC model, comprising of the geometrical and functional information necessary for the description of the identified

[5] https://mosquitto.org/ - (accessed 14/07/2023)

[6] https://www.influxdata.com/; https://www.influxdata.com/time-series-platform/telegraf/ - (accessed 14/07/2023)

workspaces, forms the foundation of the workplace digital twin knowledge base. Dedicated platforms' functions retrieve sensors' and workers' data from the timeseries database and stores them as RDF triples accordingly to the SSN ontology. In turn, the building information contained in the IFC model are mapped to BOT ontology classes (i.e., `bot:Space` and `bot:Element`) and linked to sensors' observations and workers' features, preferences, activities and feedback according to the WOMO ontology. Eventually, the resulting knowledge graph can be queried within the platform, and dedicated services provide for the visualization of the results to support workplace performance assessment use cases.

5. CASE STUDY

In this section, the capabilities of the presented prototype are demonstrated with a room-scale case study that involved the collection of worker feedback and sensor data over a period of one week. The collected data are integrated with static workplace information stored in a correspondent ICDD container (e.g., IFC model), then queried and visualized for a performance assessment use case using the dedicated web platform. The appointed room is a shared office in availability of the Chair of Computing in Engineering at the Ruhr University Bochum (Bochum, Germany). The office and case study setup specification are shown in Fig. *4*.

Workspace specification

Workspace type	Shared office
Workstations (Employees)	4 (4)
Lenght x Width x Height	7,35 x 6,00 x 3,75 m
Area	44,10 m^2
Volume	165,38 m^3

Observed properties & Sensors

Air temperature and relative humidity	1x Temperature and humidity sensor (height = 0,70 m)
Occupancy number	4x Presence sensor (1x workstation)
Window status	2x Contact sensor (1x window)

Sensor network characteristics

Network coordinator	Raspberry Pi 3 Model B connected via ethernet to internal network
Zigbee gateway	Phoscon ConBee II Universal USB Zigbee 3.0 gateway

Worker feedback colletion

Workers involved	4 - Allocated to the office
Feedback strategy	Web application (browser) Voluntary (>= 4 times/day)
Test duration	1x Work week (10-14/07/2023)
Worker data	6 - ID, location, activity category and type, thermal preference, self-assessed productivity

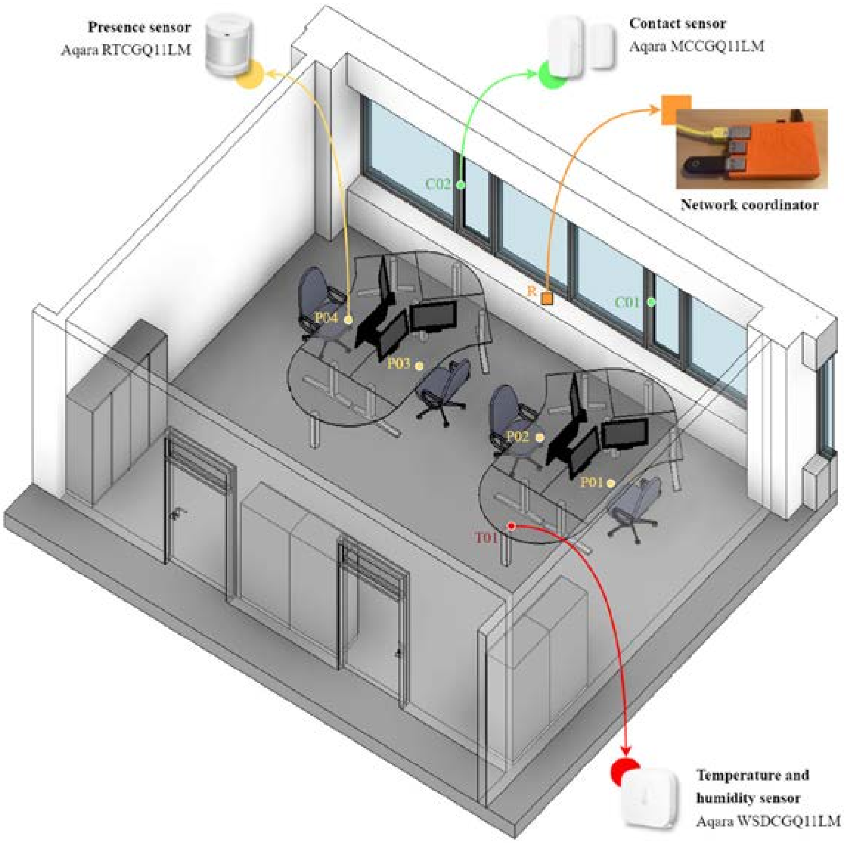

Fig. 4 Case study setup

5.1. Sensor network setup

The deployed sensor network consists of commercial products based on the Zigbee standard and widely adopted in smart building applications. The main characteristics of the installed components are reported below, along with their vendor and model to allow for specification retrieval:

- *Air temperature and humidity sensor (x1)* – It is positioned under the work plane of one of the desks in order to: avoid direct exposure to sunlight or radiators' heat emission; avoid obstruction to other objects; observe occupants' thermal micro-environment (i.e., height 0,70m) during work without being exposed to their body heat emission. [Aqara WSDCGQ11LM]
- *Contact sensor (x2)* – They return the open/closed status of each operable window. [Aqara MCCGQ11LM]

- *Motion sensor (x4)* – They use passive infrared (PIR) detection and are positioned under each of the desks' work planes. The sensor field-of-view is partially obstructed so that the detection of false positives is minimized. Presence at workstations is aggregated to determine room occupancy. [Aqara RTCGQ11LM]
- *Network coordinator* – A Phoscon ConBee II universal USB Zigbee 3.0 gateway connects the sensors and can support other Zigbee compatible devices from different vendors. The gateway is installed on a Raspberry Pi 3 Model B, connected via ethernet to the backend. In turn, on the Raspberry Pi runs an open source Zigbee2MQTT[7] bridge that enables network configuration (i.e., device pairing, removal and setting) with a graphical user interface accessible via browser. The bridge encodes the incoming sensor data into MQTT messages that are published to the Eclipse Mosquitto MQTT broker instance at the backend. The topics' hierarchy focuses on the sensors, and presents three levels: argument, sensor type and ID (e.g., "sensors/contact/c01" for contact sensor "C01"). Therefore, decoupling the sensors' deployment from the network configuration, higher flexibility is provided. Sensor metadata (e.g., observed window) are stored in the workplace knowledge graph.

Eventually, an InfluxDB agent, telegraf, is configured to connect to the MQTT broker, subscribe to all the topics of interest (i.e., "sensors/#"), decode sensor messages' payloads and write the related observations in timeseries within the predisposed sensor bucket.

5.2. Worker feedback web application

The collection of workers' feedback involved the four employees assigned to the case study office for one week (i.e., five workdays, 10-14th July, 2023). A web application has been implemented to collect their momentary feedback as responses to a single-page survey form (Fig. 5). Survey fatigue bias has been minimized presetting the workers' IDs and location and limiting the survey's queries to three. First, the specification of the current activity category and type is requested among five options: solo work, call, group work, break, or other unspecified activity. Then, the expression of the worker preference towards the perceived thermal quality is requested in a three-points scale: prefer cooler, no change, or prefer warmer. Eventually, the self-assessed productivity shall be indicated among not productive, normal or very productive. Rating scales' mid-points represent satisfaction with the environment and baseline productivity. To submit the feedback, at least one query must be responded. The survey response data are posted to Influx DB and stored as timeseries in the dedicated feedback bucket. The subjects involved have been informed about the research purposes, have agreed to voluntarily provide the feedback data and allow for their anonymized use and dissemination.

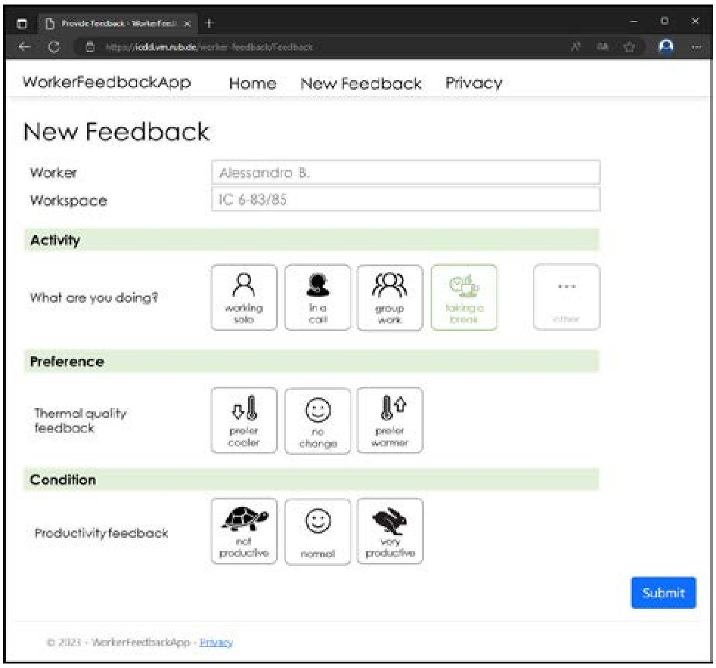

Fig. 5 Worker feedback web application – Survey form

[7] https://www.zigbee2mqtt.io/ - (accessed 17/07/2023)

5.3. Workplace performance assessment

The case study evaluation of the workplace digital twin prototype has been carried out in terms of its capabilities of integration, querying, and visualization of heterogeneous data (i.e., sensors, workers, building) for workplace performance assessment. For this purpose, a use case related to the assessment of the perceived thermal quality has been specified in form of the following competency questions (CQs):

CQ1: *How has a workspace performed for thermal quality in a certain period?*

CQ2: *Which workspace's environmental conditions are related to the reported thermal preferences?*

To address the above CQs, a customized "workplace performance dashboard" service has been implemented within the discussed ICDD web platform (Fig. *6*). On the left-hand panel an authorized user can retrieve and access all the resources and contents organized in separate ICDDs containers, one for each identified workspace (i.e., case study office "IC6-83+85"). In the *Ontology Resource* folder, the data structures necessary for the semantic formalization of the containers contents, link and domain knowledge are stored. The *Payload documents* folder contains the workspace IFC model and the proxy documents corresponding to each installed sensor. In turn, these can be accessed to retrieve the related observations from the timeseries database. Besides, the reified worker, feedback, sensor data and internal links are stored in the *Payload triples* folder.

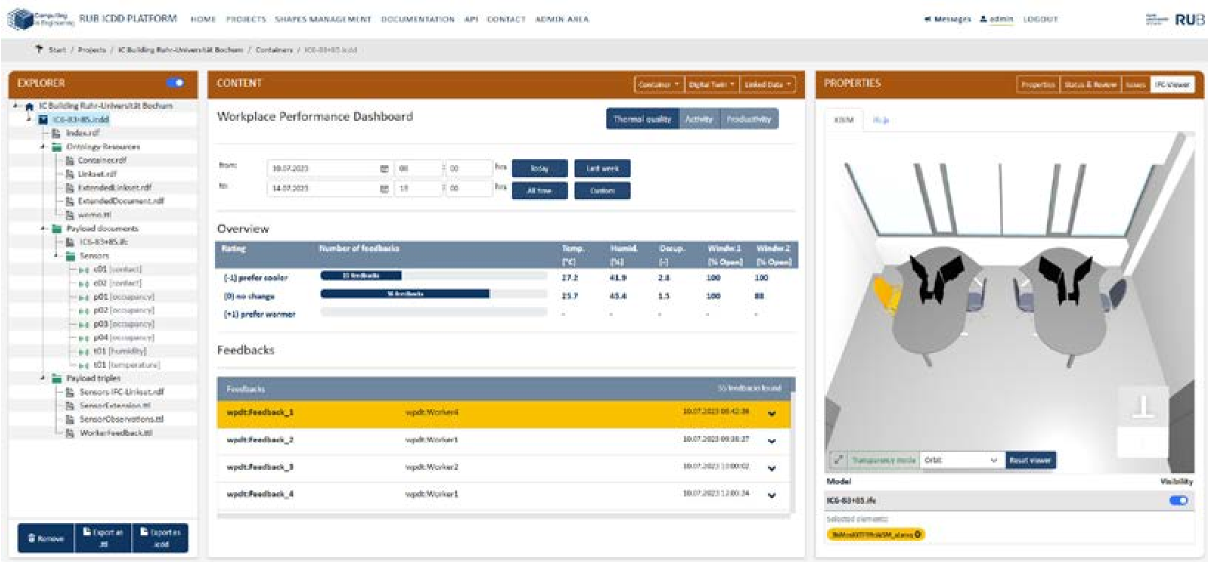

Fig. 6: Workplace performance dashboard (ICDD web platform)

In the central panel the user is provided with a graphical interface for querying and visualizing the data. The proposed approach for workplace performance assessment is centred on the evaluation of the conditions perceived by the employees and expressed with their feedback responses, hence the user has two filtering options to reduce the scope of the query: first, the object of the assessment must be chosen among preferred workspace environmental properties, activities performed by the workers or their experienced conditions; then, the target time interval must be specified. For the presented use case, feedback data are filtered for *thermal quality* preferences expressed within the data collection period of 10-14th July, 2023. In the *Overview* section the distribution of the responses is then returned according to the adopted rating scale and in relation to the mean values of the sensor observations at the corresponding feedback times. Therefore, the manager can not only assess the workplace performance in terms of overall thermal quality (CQ1) but also understand which conditions contributed the occupants' thermal comfort and take better informed actions to mitigate the occurrence of unsatisfying conditions (CQ2). In this regard, the bidirectional link established between the sensor and feedback data with the corresponding element of the workspace IFC model showed in the right-hand viewer contributes to enhance the visualization of the queried data. In fact, selecting one retrieved feedback instance the workspace element related to its source location is highlighted; conversely the selection of another linked element in the model can be used for further filtering the query results (i.e., per workstation).

6. CONCLUSIONS

The improvement of workers' well-being and productivity in existing indoor workplaces can be achieved with the adoption of occupant-centric approaches based on the understanding of the complex building/worker interactions. For this purpose, this paper presents the concept of a semantic digital twin that enables the linking and contextual interpretation of building, sensor, and worker data to support workplace management use cases. The system requirements are identified along with a comprehensive four-layered architecture, and the system's prototypical implementation is discussed. The adoption of commercial Zigbee devices and the MQTT standard protocol for data communication are proved effective for the deployment of an affordable, flexible, and scalable sensor network. An InfluxDB database is implemented to efficiently store and easily access both sensor and feedback timeseries data, the latter collected with a custom developed web survey application. The core digital twin services related to the semantic integration, querying and visualization of the heterogeneous workplace data are realized with the adoption of standardized ICDD containers and Semantic Web technologies, enabled through a custom developed web platform. Eventually, the system prototype's capabilities for the assessment of workplace performance are demonstrated with the correlation of workers' thermal preferences and workspace condition observed for the case study.

At this development stage, the proposed concept still presents several limitations that shall be addressed with further research. The extension of the digital twin prototype in terms of number of monitored workspaces, building and worker features considered, employees involved, and feedback collection period is currently undergoing to test it against a building-scale application scenario. Furthermore, additional platform's services are under development to investigate semantic reasoning opportunities that the system can provide for workplace issue discovery and spatial recommendations.

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A SYSTEMATIC REVIEW OF DIGITAL TWIN AS A PREDICTIVE MAINTENANCE APPROACH FOR EXISTING BUILDINGS IN THE UK

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ABSTRACT: *Digital Twin (DT) developments and applications in the Architectural Engineering Construction (AEC) Industry are emerging. However, insufficient publications synthesised the existing literature on DT of existing buildings, including energy retrofit and challenges as part of Net-zero strategies. When developing DT systems, it is vital to include the existing buildings primarily captured in 2-Dimensions (2-D) static data. To date, the implementation of DT has been minimal in applications in existing buildings in the UK. Despite DT benefits for maintenance (O&M) managers, facilities management (FM) as a comprehensive source of consistent data for predictive maintenance. This study explored the challenges faced by DT adoptions in existing buildings through a systematic review of the extant literature. A systematic approach is adopted to search the Scopus database using relevant keywords such as "Digital Twin.", "Built Environment" and "Existing Buildings.". the study focused on publications from the past five years (2018 to 2023) and prioritised articles in Scopus. The findings of this paper showed that the practitioners, O&M managers, and academics in built environments need more proper knowledge and technical expertise on digital twins as part of Industry 4.0 (I4.0). Evidence from the literature resulted in low empirical case studies and applications. The complexity of real-time data integration and interoperability were highlighted as part of the challenges despite the need for comprehensive knowledge of DT in the built environment. Scarce publication on the study was noted. The directions for comprehensive solutions and future research on digital twin applications in existing buildings towards achieving efficient energy retrofits, cost reductions, and net-zero goals were highlighted.*

KEYWORDS: *Digital Twin, BIM, Data, Buildings, Energy, Management.*

1. INTRODUCTION

The emergence of Industry 4.0 has shifted the trajectory in the built environment. Digital Twin (DT) is essential to implement Building 4.0 (Delgado et al., 2023). There is more interest in DT technology as a building block of the metaverse and a vital pillar of Industrial 4.0 that needs to be harnessed (Hassani, Huang, & MacFeely, 2022). What is the place of DTs in constructed facilities projects? (Khallaf, Khallaf, Anumba, & Madubuike, 2022). The Digital Twin framework is based on Building Information Modelling (BIM) and a newly created plug-in to receive real-time sensor data from the physical instance (H. Hosamo, Hosamo, Nielsen, Svennevig, & Svidt, 2023). The built environment needs to move from a static sustainability assessment to a DT- based and IoT dynamic approach to turn climate and environmental challenges into opportunities and support the sustainability decision processes throughout the whole building's life cycle (Tagliabue et al., 2021). DT has become a 'hot topic' among academic circles and commercial communication in the industry. However, the DT is often misunderstood or misused as it is 'trendy'(Zhou, Zhang, & Gu, 2022).

Why DT instead of a traditional monitoring system? Traditional or human monitoring systems resulted in wastages, siloed documentation, and incorrect monitoring activities (Agrawal, Thiel, Jain, Singh, & Fischer, 2023; Khalil, Stravoravdis, & Backes, 2021; Sagarna, Otaduy, Mora, & Leon, 2022). Change is required, and DT could solve these problems better. The awareness of the interaction of humans and DT is vital to eliminate costs, strategic misalignments, misallocation of resources, and unrealistic expectations from DTs due to DT technology's immaturity (Agrawal et al., 2023).

DT is needed for prediction and stimulation due to the inability of the 2-Dimensioal (2D) or 3-Dimensional (3D)-BIM) data on its own to give a suitable platform for prediction. The local and global market dynamic changes require more robust and innovative operational BIMs in the AEC-FM sectors. The static 3D model needs an active approach (Harode, Thabet, Jamerson, & Dongre, 2023). However, the existing maturity models lack DT implementation comprehensively and quantitatively (Chen et al., 2021). The levels and advancement of digitalisation in the AEC industry have different capabilities. The AEC industry is fragmented into the pillars of

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Modupe Sobowale, Faris Elghaish, Tara Brooks, *A Systematic Review of Digital Twin as a Predictive Maintenance Approach for Existing Buildings in the UK*, pp. 1206-1218, DOI 10.36253/979-12-215-0289-3.119

Industry 4.0: the Internet of Things (IoT), big data, augmented reality, advanced visualisation, Virtual Reality (VR) and simulation, additive manufacturing, system integration, cloud computing, autonomous systems, and cybersecurity (Pour Rahimian, Dawood, Ghaffarianhoseini, & Ghaffarianhoseini, 2022). There are issues with minimising the cost and manual labour of the automated segmentation of individual instances for more efficiency and valuable outcomes for geometric digital twins (Agapaki & Brilakis, 2021).

The global goals to address environmental challenges in the construction industry and operational assets' life cycles warrant a change of approach. The concept of digital twins' application as one of the solutions has a knowledge gap for its adoption in the industry. Integrating IoT, BIM and AI as parts of the digital twin to automate the monitoring and control of emissions from existing assets evidence interactive trends and patterns from collected data through the integration of machine learning. It enhances facility management as a potential for net-zero targets. However, there are limitations, such as digital shadow usage instead of real-time digital twins (Arsiwala, Elghaish, & Zoher, 2023). Nearly Zero Emission Buildings (NZEBs), reducing the energy consumption of the existing building is necessary, and the need to manage energy consumption is supported (Agostinelli, Cumo, Guidi, & Tomazzoli, 2021; Francisco, Mohammadi, & Taylor, 2020; Kaewunruen, Rungskunroch, & Welsh, 2019; Tang et al., 2023). Still, the viability of digital twins' financial and technical implementation has been questioned. However, the BIM-Digital Twin integration for detailed energy stimulation was used in a case study in the United Kingdom (UK); it was proven that digital twin implementation has the potential for a 23-year return period for renewable technology for an existing building (Kaewunruen, Rungskunroch, et al., 2019).

The DT-based approach could provide an adaptive comfort model, energy-saving strategies, and building comfort optimisation. Exploiting the digital twin approach supports sustainability decisions through the whole adoption cycle for climate issues and environmental challenges; it can be used for energy-saving in different types of buildings (Tagliabue et al., 2021). The effectiveness of implementing a digital twin for asset management is lacking for adoption in the housing sector and industry practitioners for predictive monitoring in buildings (Arsiwala et al., 2023). Existing research indicates that DT is still needed in stimulation during system run-time and different lifecycle phases in academic and industrial communities (M. Liu, Fang, Dong, & Xu, 2021).

With all the above in mind, this paper aims to develop a direction for research on digital twin applications in existing buildings towards achieving the net-zero target. The objectives are 1) to explore the challenges in using DT in existing buildings? And 2) to investigate how the built environment sector could use predictive maintenance system-based DT in the UK. The rest of the paper sections are 2) the adopted methodology in the study, 3) digital twins research for predictive maintenance, 4) research significance and contributions, and 5) the conclusion and recommendations for future studies to leverage the adoption of DT for predictive maintenance in the built environment.

2. METHODOLOGY

According to Webster and Watson (2002), the literature review aims to uncover the past to identify the gaps and chart future directions by identifying aspects that research should focus on. The benefits of using a systematic literature review in this paper are: 1). to identify where evidence may be lacking, contradictory or inclusive, and 2). justify why a problem is worthy of further study (Aromataris & Pearson, 2014). See Figure 1.

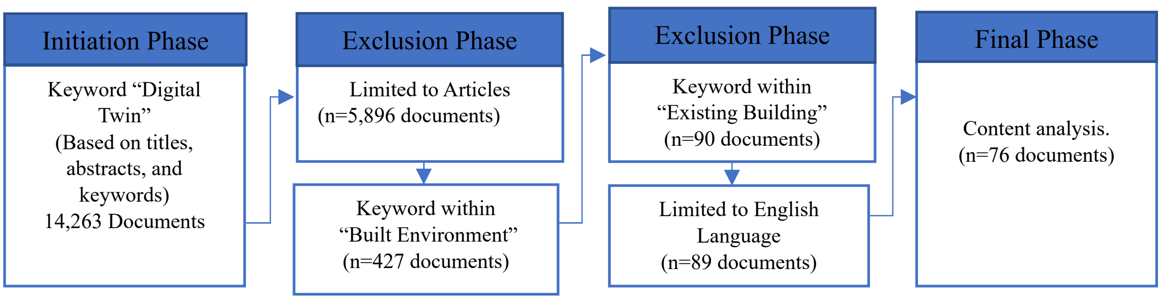

Fig 1: Systematic Selection Flowchart

The systematic review methods framework is based on the Initiation, Exclusion, Exclusion and Final phases criteria based on research studies by Kitchenham et al. (2010) and Mastan, Sensuse, Suryono, and Kautsarina (2022). For the inclusion and exclusion stage, Scopus was used to filter relevant keywords for the study to reduce the likelihood of bias, as the largest database of peer-reviewed research compared with Google Scholar or Web of Science and PubMed. The keywords searched from titles and abstracts were "Digital Twin", "Built Environment", and "Existing Building" as the relevant terms to the research study and the domain, which were used on papers published over a timeframe between 2018 and the present.

Articles were chosen from different journals written in English. The selected articles were then narrowed to 76 articles in the Scopus database using the process described in Figure 1. The articles were categorised broadly into 1). BIM-DT Maturity Model 2). DT in the AEC industry 3). DT for Maintenance of Buildings 4). DT for Net Zero in Existing Buildings (NZEB) 5). DTs for Facility Management 6). DTs for Energy Management. However, the emphasis was an overview analysis of the DT technology for existing buildings management within the AEC industry. NVivo software was used for the systematic content review and visualisation analysis. The NVIVO software aided rigorous data extraction, evaluation, and categorisation of the large amount of data generated by the 76 selected articles.

3. DIGITAL TWINS RESEARCH FOR PREDICTIVE MAINTENANCE

The following sub-sections will show cases of the attributes and challenges of DT adoptions within the articles selected. These are: 1). BIM-DT Maturity Model 2). DT in the AEC industry 3). DT for Maintenance of Buildings 4). DT for Net Zero in Existing Buildings (NZEB) 5). DTs for Facility Management 6). DTs for Energy Management for an overview of limitations faced within the built environment.

3.1 BIM-DT Maturity Model

The emergency of real-time connectivity and deployment in an environment increases the potential for DT concepts in the built environment. Noted to be in an early stage of adoption, the analysis indicated unrealised and unexploited possibilities of the DT concept for building management; further studies as a baseline were recommended (Deng, Menassa, & Kamat, 2021). BIM and DTs are disruptive technologies to be embraced by the construction industry due to the recent increase in advanced automation and autonomous technologies at the organisation, and need to be adequately leveraged (Sepasgozar et al., 2023). Notably, DT proved to be a valuable tool for the entire lifecycle management of buildings since BIM cannot handle the sensory information and complexities of existing buildings (Banfi, Brumana, Salvalai, & Previtali, 2022).

Existing BIM standards (ISO 19650) were proposed to promote a better interoperable digitalised built environment to develop DTs in the AEC sector (Nour El-Din, Pereira, Poças Martins, & Ramos, 2022). DT-BIM-based model reduced load bearing and risk in existing highway infrastructures. However, concerns were information collection and analyses for inspection, maintenance planning, and data sharing and visualisation limitations. The BIM-based model provided solutions and insights for high-quality construction and maintenance to minimise rapid degradation and component failures in infrastructures. Owners and stakeholders would achieve higher operational efficiency and sustainability outcomes over the life cycle, especially the expensive phases (Kaewunruen & Lian, 2019). DT-BIM-based model is recommended for the whole life-cycle mitigation of risks and uncertainties of exposure to extreme weather conditions for construction industry stakeholders (Kaewunruen, Sresakoolchai, Ma, & Phil-Ebosie, 2021).

Integrations of human-centred approaches, Virtual Design Construction (VDC), digital twin and artificial intelligence will transform the future of the AEC industry and create research opportunities. The integrations can simultaneously optimise, predict, and provide significant cost savings for the industry work processes, which should be noted for the main line of future research (Rafsanjani & Nabizadeh, 2023). BIM, IoT, and AI-supported systems are beneficial for prediction and data-driven retrofitting strategies, a step towards achieving the net-zero targets (Arsiwala et al., 2023). Multi-layer DT called BIM-IoT-Data integration (BIM-IoTDI) indicated capabilities to overcome interoperability and be suitable for smart buildings (Eneyew, Capretz, & Bitsuamlak, 2022). AI, DTs, and scanning technologies are valuable for maintenance strategies. However, some challenges are associated with technological, cultural, market and regulatory factors (Çetin, Gruis, & Straub, 2022).

Two-directional interactions between humans and computers should be part of the development to reach a high maturity level. Further studies, including advanced technologies like AI, BIM, and Geographic Information System (GIS) cloud computing, are essential to cope with the complex urban challenges of multidisciplinary DTs (Masoumi, Shirowzhan, Eskandarpour, & Pettit, 2023). Automation and robotisation are resources for management improvement in construction and existing buildings-the BIM data are programmed to a robot and visual format as the digital twin of the real-world building revealed valuable results that need further studies on the data reliability, interoperability of the BIM and 3D-Robot connections, and update of the BIM model based on robot feedback (Pauwels, de Koning, Hendrikx, & Torta, 2023). Likewise, the Mobile BIM Technology (MBT) functions can help researchers and practices in digitalisation, lean construction, evaluation perspectives and data-driven approaches to enable DT. Legal and security perspectives should be considered (Jowett, Edwards, & Kassem, 2023).

The proposed DT and Cloud BIM-Extended Reality (XR) platform development using the Scan-to-BIM-to-DT process to a 4D multi-user live app to improve building comfort, efficiency and costs was validated for energy improvements for existing buildings and façade renovations (Banfi, Brumana, Salvalai, et al., 2022). Implemented DT used scan-to-BIM with sensor data as an Industry Foundation Classes (IFC) BIM platform to monitor the structural health of the building walls. It can benefit FMs for planning and maintenance activities and the long life cycle of a building (Longman, Xu, Sun, Turkan, & Riggio, 2023). The lack of a clear process roadmap is partially a factor. Still, Digital Twin Construction was proposed as a comprehensive construction mode that prioritises closing the control loops instead of an extension of BIM tools integrated with sensing and monitoring technologies (Sacks, Brilakis, Pikas, Xie, & Girolami, 2020). DT cannot be limited to the focused aspects like 3D modelling, monitoring, and visualisation of DTs (Masoumi et al., 2023). Tagliabue et al. (2021) supported shifting from a static sustainability assessment to a digital twin-based and IoT-enabled dynamic approach for real-time evaluation, sustainability criteria control, and user-centred viewpoint in the built environment. A roadmap is required to support decisions and policymakers to aid implementations for the next ten years (2030) (Sepasgozar et al., 2023).

It should be noted that DTs are extensions of engineering information (EI) leveraging modern information and communications technology (ICTs) and do not have their unique technical characteristics (Zhou et al., 2022). The integration of DT roles as an observer, analyst, action executor and decision-maker is useful in helping practitioners systematically plan DT deployments, clearly communicate goals and deliverables, and lay out a strategic vision (Agrawal et al., 2023). Digital Twins are the future of the metadata required for a socio-technical collaborative and sustainable ecosystem based on a virtual representation of the physical instance in a real-time operational state superseding static 3D- Building Information Modelling or traditional 2D of assets for the multidisciplinary AEC domains for operational efficiency and cost reduction (Pregnolato et al., 2022) updated information to analyse and optimise ongoing design, planning and production, lean construction, and data-centric construction management (Sacks et al., 2020).

The widespread traction of DTs for constructed facilities projects reveals the benefits of DTs as the ability to reduce operating costs and human error, automate energy demand, manage assets throughout their lifecycle, and structural health monitoring in real-time (Khallaf et al., 2022) with robot-Assisted reality capture in larger spaces (Xu, Xia, You, & Du, 2022). The application of DTs and Machine Learning helps predict and analyse prestressed steel structures needed for intelligent monitoring techniques and control methods to ensure safety (Z. Liu, Yuan, Sun, & Cao, 2022). IoT and DT connection and integration produce real environments to boost automation, Industry 4.0 transformation and cost-effectiveness (Al-Dhlan, 2021) with robot-assisted reality capture in larger spaces (Xu et al., 2022). Likewise, DTs in the UK are used for highway asset management to achieve minimum human input and have very high accuracy (Jiang, Ma, Broyd, Chen, & Luo, 2022).

Multi-layer DTs proved to be a valuable tool for the entire lifecycle management of buildings since BIM cannot handle the comprehensive DT technology that can be supported with socio-technical approaches to reach maturity. The integration of IoT with DT has proven to be valuable with the application of DTs in the multidisciplinary AEC domains, even though some challenges were indicated in Tables 1-5.

3.2 DT in the AEC Industry

The articles in Table 1 are on DT research in the AEC Industry and the challenges encountered. Infrastructure assessment and construction management were highlighted.

Table 1. Articles on DTs studies within the AEC Industry.

Author/Year	Focus of Study	Employed Tools	Challenges /Limitations
(Camposano, Smolander, & Ruippo, 2021)	Awareness of DT of Built assets relative to the software ecosystem	Interpretive analysis of semi-structured interviews	Inter-organizational relationships, data sharing, and technical expertise
(Çetin et al., 2022).	Adoptions of digital technologies in social housing	Multiple- case study Circular Economy Digital Twins framework	Technical, cultural, market and regulatory issues. Misalignment of supply and demand. Data quality and sharing
(Eneyew et al., 2022)	Interoperability of smart-building DTs	BIM-IoT Digital integration	Autonomous query decision and data sharing

(Jowett et al., 2023)	Mobile BIM technologies taxonomy in field BIM interactions with construction management functions	A longitudinal case study over 12 months, two project workshops, expert interviews and an industry survey at project, enterprise, and industry levels.	Lack of delineation between related terms used.
(Kaewunruen et al., 2021)	Vulnerability assessment and risk-based maintenance of infrastructures	BIM-DT based model	Automated interaction of data, 3D modelling human resources and standards, IT software natural and human risk assessments.
(Longman et al., 2023)	The implementation of DTs to support structural health monitoring (SHM).	Scan-to-BIM approach in IFC-BIM platforms.	Data integrations and project infrastructure
(Nour El-Din et al., 2022)	Status of DTs and the evolution of the concept of DTs for construction Assets	Systematic Review	Lack of data standardisation
(Pauwels et al., 2023).	Live semantic data transfers from building digital twins for robotic navigation	BIM-based model	Automation, data reliability and standards
(Rafsanjani & Nabizadeh, 2023)	Cost-saving DT capabilities in construction and operational phases	VDC-DT based model + VR+AR	Technical expertise, Compatible software, Automation, Human-centric scenarios, real-time data senses and analysis.
(Sacks et al., 2020)	Digital twin information systems to achieve closed-loop control systems to monitor construction.	Conceptual analysis	Lack of comprehensive information system and knowledge

3.3 DT for Maintenance of Buildings

Table 2 comprises articles on building maintenance and the challenges of adopting DTs. Emphases are mostly on historical building restoration.

Table 2. Articles on DTs exploration for maintaining structural buildings.

Author/Year	Focus of Study	Employed Tools	Challenges /Limitations
(Ali, Alhajlah, & Kassem, 2022)	The status and future trends in building information modelling (BIM)	Systematic literature review (SLR) methods through co-occurrence and co-citation analysis.	The complexity of the project, integration of components and data
(Banfi, Brumana, Landi, et al., 2022; Khalil et al., 2021)	Data categorising in the digital documentation of heritage buildings	HBIM model	Protection and longevity of heritage buildings data. Interoperability and BIM standardisation or extended reality environments and data formats.
(Cardinali et al., 2023; Moyano, Carreño, Nieto-Julián, Gil-Arizón, & Bruno, 2022; Noronha Pinto de Oliveira e Sousa & Correa, 2023).	Digital twins for heritage buildings.	Historic building information modelling (HBIM) geometric model.	Data acquisition constraints and difficulties, the scale of the building.
(Daniotti et al., 2022).	BIM-DT Based Interoperability for efficient renovation in buildings	BIM-DT based model	Data integration and standardisation processes
(Pan, Braun, Brilakis, & Borrmann, 2022)	How to enrich geometric digital twins of buildings, particularly emphasis on capturing small vital entities in buildings	3D point cloud + AI-based image segmentation	Variation in objects, data collection and occlusion of the environment
(Porsani, de Lersundi, Gutiérrez, & Bandera, 2021)	Evaluates of an automated or semi-automated BIM to BEM workflow in buildings	BIM-BEM model	Technical expertise, large and complex buildings
(Sagarna et al., 2022)	Documentation and displaying inspection-related information in BIM models to generate a dynamic information model in buildings.	Innovative BIM model-State of Conservation Assessment BIM Model (SCABIM)	Dynamic open-source data integration, technical workforce, and equipment
(Tan, Leng, Zeng, Feng, & Yu, 2022).	DT-3D digital replicas record and heritage buildings survey	BIM multi-methodological approach,	Obstruction of the surrounding environment and data exchange.

3.4 DT for Net Zero in Existing Buildings (NZEB)

Table 3 includes related articles on efforts towards NZEB and the challenges faced while adopting DTs. BIM-based models were majorly used to integrate data for simulations.

Table 3. Articles on NZEB research using DTs.

Author/Year	Focus of Study	Employed Tools	Challenges /Limitations
(Godager, Onstein, & Huang, 2021)	BIM in asset and facilities management.	Enterprise BIM (EBIM)	Data integration, security and management, Naming convention, Data infrastructures, and suitable common data environment.
(Kaewunruen & Xu, 2018)	Assessing the carbon footprints of a building in the design process using BIM technology.	BIM-enabled data visualisation + API	Computational and technical expertise, natural light area and data extraction
(Kaewunruen, Peng, & Phil-Ebosie, 2020; Kaewunruen, Sresakoolchai, & Kerinnonta, 2019)	Sustainability and vulnerability in buildings	DT + BIM	Computational and technical expertise, structural tolerances, and autonomous integration.
(Lu, Xie, Parlikad, Schooling, & Konstantinou, 2020)	BIM to digital twins for operation and maintenance	Smart asset management (DTs + AI + ML+ data analytics)	Technology, Organisation, information, and data standard-related issues. Domain alignment, Interaction between domain and all stakeholders
(Ochs, Franzoi, Dermentzis, Monteleone, & Magni, 2023)	Monitoring and simulation-based optimisation of two multi-apartment for NZEBs	MATLAB Simulink simulation +Building management system	Cost analysis, different heat sources, and simulation
(Shen, Ding, & Wang, 2022)	Whole-life-cycle net-zero-carbon buildings	DT +BIM	Building lifecycle stages. Automated system and dynamic sensor data

3.5 DT for Facility Management

Related articles on building facility management and the challenges of adopting DT approaches are in Table 4. Studies were mainly based on existing buildings' operation and maintenance phases.

Table 4. Articles on facility management research using DT.

Author/Year	Focus of Study	Employed Tools	Challenges /Limitations
(Badenko et al., 2021)	Integration of digital twin and BIM technologies in FM	DT +BIM ("Factories of the Future" framework)	Systems integration, Training and investment cost and technical expertise
(Chacón et al., 2023)	Structural Health Monitoring (SHM) systems within the DT platform	BIM -DT-based model	Data integration and interoperability, and multiple sources pipelines.
(Chen et al., 2021)	An innovative maturity model for measuring digital twin maturity for asset management.	DT +BIM (Gemini Principles)	Domain environment, technical expertise, Cultural and policy influence
(Costa, Arroyo, Rueda, & Briones, 2023)	A ventilation early warning system (VEWS) for FM	Smart Campus Digital Twin (SCDT) framework (BIM +IoT +AI)	Characteristics of building workspaces, data integration and interoperability of systems
(Fialho et al., 2022)	Prototyping a BIM and IoT-based smart lighting maintenance system for the FM sector	BIM and IoT-based	Lack of consistent tools, methods, and devices for measuring building components' performance and restrictions in research resources
(Harode et al., 2023)	System architecture for a digital twin in a healthcare facility (FM)	Structured literature search and analysis +DT	Data integration, standard, environment, interoperability, and technical expertise
(H. H. Hosamo, Nielsen, Kraniotis, Svennevig, & Svidt, 2023a, 2023b)	Automated fault source detection and prediction for comfort performance evaluation of existing buildings	DT + BIM model based on Bayesian networks (BNs).	IoT connectivity, BIM systems, technical and computational expertise, interoperability of systems, occupant profile and owner funding.
(Jiao et al., 2023)	A sustainable digital twin (DT) model of operation and maintenance for building infrastructures,	DT +Bayesian network (BN) + Random Forest (RF)	Small buildings, equipment, building space, data collection and systems

(Khajavi, Tetik, Liu, Korhonen, & Holmstrom, 2023)	DT for safety and Security in building Lifecycle	DT +BIM	Awareness, cost, data type, real-time studies, and access to case studies on other buildings
(Levine & Spencer, 2022)	Post-Earthquake Building Evaluation.	BIM-Based Digital Twin Framework	Building components and alignment, BIM systems and computational systems
(Lu, Xie, Parlikad, & Schooling, 2020; Xie, Lu, Rodenas-Herraiz, Parlikad, & Schooling, 2020)	Visualised inspection system for monitoring during daily Operation and Maintenance	AR-supported automated environmental anomaly detection and fault tree analysis method	Environmental conditions, Data collection, processes, and computational expertise
(Moretti, Ellul, Re Cecconi, Papapesios, & Dejaco, 2021)	Integration of GIS and BIM for built environment condition assessment in asset management decision-making	DT +BIM +GIS (Geographic Information System)	Technical complexity, digital expertise, automatic semantic mapping, stakeholders, information gathering, data and systems integrations
(Pan, Braun, Borrmann, & Brilakis, 2022)	How to generate geometric digital twins of the indoor environment of buildings automatically.	3D deep-learning-enhanced void-growing approach	Computational efforts, point cloud data and occlusion of the environment
(Rampini & Re Cecconi, 2022)	Artificial intelligence in construction asset management for sustainability	Literature review +bibliometric analysis	Time-consuming and labour-intensive, technical expertise, Data collection and processes
(Shahinmoghadam, Natephra, & Motamedi, 2021)	The benefits of BIM, the IoT and Virtual Reality (VR) for thermal comfort conditions	BIM+ IoT +VR	Sensor placement, Building space, and semi-automated registration of the thermal image's method

3.6 DT for Energy Management

Articles focusing on the efficiency of building energy management and the challenges of adopting DT approaches are in Table 5, exploring energy cost and consumption reduction.

Table 5. Articles on energy management research using DT.

Author/Year	Focus of Study	Employed Tools	Challenges /Limitations
(Borja-Conde, Witheephanich, Coronel, & Limon, 2023).	Automatic thermal models of existing buildings for energy management	High-fidelity simulator software TRNSYS	ML techniques, the accuracy and robustness of building thermal behaviour modelling
(Corrado, DeLong, Holt, Hua, & Tolk, 2022).	Green metrics and digital twins for Sustainability planning and governance	Published literature review	Real-world metrics standard, computational decision support
(Delgado et al., 2023)	The interconnection between BIM and building energy modelling (BEM) for energy cost reduction.	BIM-BEM (Drone based) framework	Technical expertise and occlusion of the environment
(H. Hosamo et al., 2023).	A digital twin of heating, ventilation, and air conditioning for optimisation of energy consumption and thermal comfort based.	BIM +DT (MATLAB + Artificial neural network + multi-objective genetic algorithm)	Data standards and type, Ontology techniques to integrate BIM, energy management, and thermal comfort data in one framework.
(Hosseinihaghighi et al., 2022)	Assessment of housing stock and smart thermostat data in support of energy end-use mapping and housing retrofit program planning	Smart thermostat integration model	Data quality and collection, Classification standard terminology, occupants' behaviours, Building characteristics, real-time data integration and interoperability
(Kaewunruen, Sresakoolchai, et al., 2019)	Reconstruction design of an existing building energy building goal	BIM-based digital twin	Data integration, financial analysis, different functions of renewable technologies, and computational supports.
(Lamagna, Groppi, Nezhad, & Piras, 2021).	Digital twins for smart energy management system	A comprehensive literature review	Big data, communication protocols, lack of regulation and a transparent market, uncertain and unclear framework, different versions of DTs and algorithms.
(Spudys et al., 2023).	Operational energy performance of buildings with the use of digital twins	DT model	Lack of required equipment, digital environment, infrastructure, occupant behaviour and building automation systems

(Tang et al., 2023).	Vertical greenery system (VGS) renovation for building energy efficiency analysis based on digital twin	DT + BIM model	Direction and location of the building and environmental conditions
(Zhao et al., 2022).	Evaluation of public toilet ventilation design schemes through a digital twin to maintain high environmental quality	BIM-based digital twin	Building cost and construction simulations computations, cloud-based services, computations support

4. RESEARCH SIGNIFICANCE AND CONTRIBUTION

The research's significances are to remove silos and allow data and information sharing for effective and holistic implementation and interactions that reduce wastage and costs in retrofitting and energy consumption in existing buildings as one of the largest energy consumptions. The research would add insights into energy retrofit and management cost as part of Net-zero strategies in the UK.

Analysing the existing literature on DT attributes and challenges provides a glimpse into the reality of insufficient research studies on DT globally, especially in the UK; 25 articles from the UK were within the research scope. The analysis would contribute to the body of knowledge in the UK and globally. The literature pointed out the confusion of DT as an extended branch of BIM. However, DT has been revealed as a multi-objective and multi-scale technology field within the I4.0 that requires an advanced analytical approach through data and stimulation to support comprehensive and predictive decision-making to save costs and wastages. The door is widened for researchers to explore viable solutions to overcome the challenges uncovered in the literature to leverage DT benefits within the built environment.

The research would contribute and benefit suppliers (technologies and platforms), homeowners, landlords, policymakers, operation and maintenance (O&M) managers, facilities management (FM), and the research community to reduce costs with predictive decisions based on proactive maintenance rather than reactive maintenance. It will replace speculative retrofitting actions with factual insights for different types of existing structural buildings, occupancy behaviour and locality. There are reasonable limitations within the period of the systematic review and the platform used to select optimal articles based on the research topic due to the low number of publications. However, more publications could have been added from other platforms like Google Scholar but not peer-reviewed to ascertain the quality required to maximise the value of the review.

5. CONCLUSIONS AND FURTHER RESEARCH

Digital Twins can integrate information from multiple sources to replicate the operation of the physical spatial asset in real-time for stimulations and predictive insights**.** The application of digital twins is still in an emergency phase as a valuable digital technologies advancement, especially with the built environment and the AEC industry in the UK. There needed to be more publications on the research topic. The paper set out two objectives: 1) to explore the challenges in using DT in existing buildings. And 2) to investigate how the built environment sector could use predictive maintenance system-based DT in the UK.

DT needs to be more understood and consistent in the application or technical tools usage from literature. In addition, practitioners, AEC managers and academics need more proper knowledge and technical expertise on digital twins as part of the I4.0, as evidence from the literature resulted in low empirical case studies. The complexity of real-time data integration and interoperability were highlighted as part of the challenges. Digital Technologies can be pardoned as a common word for I4.0, are the enabler of all societies and organisations' productivities, previously a buzz, now overtaken by Artificial Intelligence (AI). The direction to advance digital twins' adoptions in existing buildings towards achieving net-zero goals is realism 1). Training for applicable practitioners in the built environment for the AEC industry. 2). Affordable computations and simulation tools and systems 3). Cloud-based architecture infrastructure and services 4). Data integration and interoperability 5). Open sources collaboration 6). Socio-technical influences and sustainable policies.

Finally, based on the literature, predictive maintenance system-based DT with intelligent analysis supported comprehensive and consistent solutions for rehabilitation, operation, and maintenance management of existing building life cycle management. However, more steps are needed to leverage the benefits: the future case study for the built environment sector to use predictive maintenance system-based DT in the UK are 1). the depth of knowledge of DT with professionals in the built environments, 2). A standard benchmark framework for DT adoptions 3). Available and accessible computations simulation tools, and systems 4). Funding for the research 5). Socio-Technical influences and training.

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PROJECT MANAGEMENT INFORMATION SYSTEM (PMIS) DASHBOARD AS A DIGITAL TWIN TO ENHANCE INFRASTRUCTURE PROJECT DELIVERY: A CASE STUDY OF AMERORO DAM PROJECT

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ABSTRACT: *In supporting the economic growth, Indonesian government has instructed to develop 201 National Strategic Infrastructure Projects, including Ameroro Dam Project. Located in Southeast Sulawesi, the construction process faced many engineering challenges with conventional monitoring methods, such as potentially delayed action plan and hindered decision making due to insufficient progress visualization data, inadequate real-time monitoring data, and unintegrated engineering data. Therefore, Project Management Information System (PMIS) dashboard is utilized as a Digital Twin innovation to overcome these challenges and optimize the project delivery. This study presents a case study approach on how PMIS could optimize the progress monitoring in Ameroro Dam Project. This PMIS Dashboard is integrated with Building Information Modelling, Digital Survey, Geospatial Data, and Project Management Data that supports the decision making as it provides more reliable data. This study illustrates the comparative study between conventional method and PMIS efficiency for a better project management. The effectiveness of PMIS can be seen as the integrated data is utilized to plan a construction working methods, along with monitoring the project schedule. Moreover, the visualization helps the engineers for a risk mitigation with the project performance display. Eventually, the paper concludes by the PMIS dashboard optimization for real-time progress monitoring in dam project, leading to more efficient infrastructure construction project management.*

KEYWORDS: *BIM, Digital Twin, Construction Working Methods, Geospatial Data, Progress Monitoring, Project Management.*

1. INTRODUCTION

As an agricultural country, the presence of Dam has always been considered as one of the most important infrastructures in Indonesia. As one of the most crucial engineering infrastructure, Dam is primarily used for water supply, flood control, agricultural irrigation, and hydroelectric power generation (Kalkan, 2014). Despite its many functions, the construction of Dam project is considered very complex. The construction of Dam project involves a large number of people with various objectives, interest, and disciplines to perform interdisciplinary activities. Moreover, time and physical resources limitations have added another dimension of complexity for dam project (Mahato & Ogunlana, 2011). However, many construction projects in Indonesia still apply traditional methods of project management which frequently caused a low productivity and waste a significant amount of time and resources due to poor prioritization and poor multi-tasking. Not only in Indonesia, but globally, construction is one of the biggest industry in the world that matters for the world economy. However, it has a long record of poor productivity. McKinsey (2020) reports the construction industry represents 13% of global GDP, but the productivity growth in construction only reach 1% annually for the past two decades. As shown in Figure 1, is significantly less than the productivity growth of the global economy, approximately 2.8% a year.

The low productivity in construction caused by many factors, one of which in slow innovation and digitalization. As it can be seen on Figure 2, the digitization index in construction is ranked as the lowest 2 among other industry. Currently, many construction projects are still using traditional monitoring systems which is impossible to implement timely checks and repairs (Woo, 2010). Previous studies also identified several limitations of conventional monitoring methods such as the absence of project visualizations that can hinder the decision making, affected the project quality, time, and costs.

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)

Rizky Agung Saputra, Agung Fajarwanto, Amy Rachmadhani Widyastuti, Sari Gita Wardani, Danang Aris Munandar, Herdy Setiawan, Abdul Rahman Kadir and Amar Muhammad Yunus Amar, *Project Management Information System (PMIS) Dashboard as a Digital Twin to Enhance Infrastructure Project Delivery: A Case Study of Ameroro Dam Project,* pp. 1219-1232, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.120

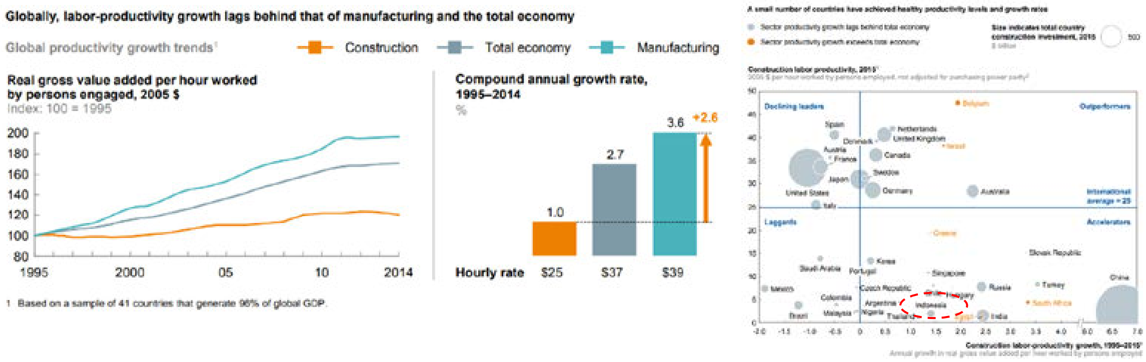

Figure 1. Global Labor Productivity Data (McKinsey Global Institute, 2017)

Figure 2. Industry Digitization Index (McKinsey Global Institute, 2016)

As the construction projects are getting more complex, it needs more advanced and integrated tools to improve the construction process. Along with the advancement of information technology (IT) that have been rapidly evolving, Digital Twin and Building Information Modelling (BIM) are some of the latest technologies that are useful in terms of improving project management in construction. Digital Twin can be referred as a concept originated with the Internet of Things (IoT) that represents digital simulation within an IT platform by integrating physical feedback data, artificial intelligence (AI), and machine learning (Bi, 2022). Furthermore, Digital Twin contributes to smart construction in achieving economic and sustainability goals (Istanbullu, Wamuziri, & Siddique, 2022). As it improves the productivity in construction sector through digitalization, many studies discussed about the implementation of Digital Twin and BIM in the construction project. However, the least amount of research discussed the best practices of Digital Twin utilization for infrastructure project management, specifically dam project. Therefore, this paper aims to perform a digital construction innovation namely Project Management Information System (PMIS) dashboard as a Digital Twin platform and analyze the project management effectiveness based on a real case study of a dam project. Finally, some recommendations of PMIS future development are proposed in the conclusion for future infrastructure projects.

2. LITERATURE REVIEW

2.1 Project Management

In order to success in delivering the expected project delivery, a good practice of project management should enable organizations to execute the project effectively and efficiently. Project management can be described as the implementation of knowledge, skills, tools, and techniques to project activities to meet the project requirements. Project management is accomplished through the correct execution and integration of the project management process identified for the project (Project Management Institute, 2017). Especially for construction project which involves many aspects, a good project management practice is required to ensure the project can be delivered on time. Moreover, construction project management can be described as a multidimensional discipline that requires accurate consideration of various crucial aspects, including cost, quality, schedule requirements, as well as social and environmental impacts, and broader stakeholder interests (Ke, Zhang, & Philbin, 2023).

2.2 Project Monitoring

To achieve the project goals, there are several crucial things in practicing project management, one of which is monitoring. Especially for dams construction, monitoring is considered critical since deformation may occurred as a result of erosion, water load, hydraulic gradients, and water saturation (Kalkan, 2014). Besides, monitoring can be described as collecting, calculating, assessing measurement and trends to enhance the process improvements (Project Management Institute, 2017). It can be concluded that project monitoring is fundamental aspect for successful project management and decision-making. However, despite the importance of project monitoring, many construction projects currently constrained by the inadequacy of traditional monitoring system. Traditional monitoring methods are considered inaccurate, time-consuming, and labor-intensive because they rely on large-scale manual operations that will lead into project delays and cost overruns (Nakanishi, Kaneta, & Nishino, 2021). Therefore, a good project monitoring system in a complex construction project is considerably important. For instance, continual monitoring is required to give the project management team with insight into the project's health and indicates any areas that might require special attention (Project Management Institute, 2017). It is because successful construction projects are identified by the level of awareness of project progress or work performance. Moreover, a progress monitoring system should comply the information requirement for real-time progress and decision making (Teizer, Lao, & Sofer, 2007). Ideally, monitoring may fasten the decision makings with its reliable data. The monitoring activities process should enable stakeholders acquire a comprehensive overview of the project's existing condition, identify issues for corrective action, and estimate future performance in terms of time and cost (Project Management Institute, 2017). As numbers of research have been conducted to reduce the gap between traditional monitoring and real-time monitoring, several approaches have been proposed for a better project management in construction monitoring.

2.3 Project Management Information System

Semi or fully automated data collection and analysis process can be a support in making quick and accurate decisions. Fortunately, technological advancement has been striving to improve the construction monitoring system in recent years. Numerous emerging automated data collection, analysis, and visualization techniques also have been utilized to develop systems for digitized real-time progress monitoring (Nakanishi, Kaneta, & Nishino, 2021). Thus, the implementation of PMIS can be considered effective to improve the project management in a complex project. According to Project Management Institute (2017) PMIS required to collect, analyze, and use the information to accomplish the project objectives and realize the project benefits. Moreover, PMIS also provides access to Information Technology (IT) software tools such as scheduling software, that allows stakeholders to track planned dates versus actual dates, report variation between the progress performance against the schedule baseline and estimate the effects of modifications to the project schedule model. Beside the integration between the volume of data and information, PMIS also includes scheduling software that has the capability to help plan, organize, and adjust the sequence of the activities; it also expedites the process of building a schedule model by generating start and finish dates based on the inputs of activities, network diagrams, resources, and activity durations (Project Management Institute, 2017).

2.4 BIM and Digital Twin

As it can fulfill the aspects of the PMIS, the idea of collaborating BIM and GIS shows a great potential as a Digital Twin to improve the project management process. In the last few years, BIM known as a collaborative working method for the creation and management of a construction project (Acebes, Testa, Alonso, & Curto, 2023). BIM can be defined as a three-dimensional view that represents the building data to achieve the summary and integration of various information in construction (Yue, 2023). Furthermore, project progress cost, construction clashes and situation can be accessed through the animation in BIM. These functions are in line with the PMIS which include spreadsheets, simulation software, and statistical analysis tools to assist with cost estimating (Project Management Institute, 2017). However, the utilization of BIM only could not satisfy the PMIS objectives. While BIM tools provide excellent representations for product design, they often lack essential features necessary for construction when it comes to Digital Twins (Bao, Guo, Li, & Zhang, 2018). Digital Twin can be defined as a virtual representation of a physical asset that can reflect its current status. The data is collected through sensors and other monitoring devices embedded within the structure and transmitted to the virtual model in real-time (Ma, et al., 2020). The implementation of Digital twins ensures the final result to be more accurate and reliable. Through accessing to this real-time data, stakeholders can quickly identify and respond to issues as they arise, leading to increased efficiency and productivity (Jiang, Guo, & Wang, 2021). In this case, BIM can be utilized for visual management tools as the base information for Digital Twin to provide a high-level representation of buildings and their assets by integrating the physical and digital world (Hosamo, et al., 2022). Besides, Digital twin construction creates a data-centric way of construction management by combining BIM technology, lean construction thinking, the digital twin concept, and artificial intelligence (Bandara, Ranadewa, Parameswaran, & Eranga, 2023). Hence, the availability of current and historical data on the digital twin enables predictions of future behavior which beneficial for operation and maintenance phase from the infrastructure asset (Sivalingham, Sepuvelda, Spring, & Davies, 2018). Some technologies such as GIS and digital surveying are also utilized to obtain the real-time data of Digital Twin. Moreover, the presence of PMIS as digital twin may improves the overall project management performance as it displays the visualization of current project state, detect the potential risk, shows the project performance, as well as enhance the collaboration between stakeholders. However, as many observers addressed about the development of BIM and Digital Twin, none of the observers discussed about the best practices for dam project. This perspective is important since dam construction is considered very complex and required a good project management system. Hence, the proposed research is to identify the Digital Twin best practice for dam project, as well as analyzing the effectiveness for project management.

3. METHODOLOGY

The methodology used on this research is based on a case study approach of Ameroro Dam from the perspective as the general contractor for project management purposes during the construction. The obstacle inherent in the construction phase is that the monitoring process is still conventional, resulting the data obtained not being real-time, although this phase is critical for monitoring project performance to ensure quality, budget, and schedule. Therefore, the step to overcome this limitation is by doing digitalization with PMIS. The PMIS will automatically collect and process the data such as BIM Model, Digital Survey data, and project data for the input data. As the result, the PMIS platform will present the project data in a more effective way, especially to support the project management and decision-makings.

3.1 Case study description

As an agricultural country, the agricultural sector plays a crucial role and contributes to the country's economy. According to data from Central Bureau of Statistics, Indonesia produces 31,36 million rices in 2021, and the government plans to increase the rice production targets up to 300.000 tons in 2024. Therefore, to support this policy, the Ministry of Public Works mandated to construct 65 priority dams through the National Strategic Project, one of which is Ameroro Dam Project. The Ministry of Public Works assigned the construction of this project to Hutama Karya as one of the Indonesia's leading state-owned enterprises for the main contractor. Ameroro Dam is built as the 2nd dam in South East Sulawesi Province to increase the number of water reservoirs in Indonesia in order to support food security programs and water availability. This dam was designed to be a multipurpose dam, with a total capacity of 54.15 million m^3 and an inundation area of 212.89 Ha. With the project value of 38 million USD, Hutama Karya covers the scope of works namely spillway, access road, bridges, hydromechanical and electrical, and supporting and facility buildings. With a project duration of 945 days, Hutama Karya faces a complex project management to finish Ameroro Dam Project such as targeted to accelerate from the project schedule, remote access to the project, and managing communication with stakeholders in remote area. Therefore, an effective monitoring system is required by the organization to manage this project throughout the project life cycle. The required features to support the project monitoring are collected and combined into a platform to form the PMIS dashboard. The utilization of PMIS dashboard helps Hutama Karya as the main contractor to enhance the project management during the construction process. The PMIS is based on Building Information Modelling (BIM) and Geographic Information System (GIS) and is integrated with other company's strategic platforms, which supports the data requirements for the project to provide a more reliable data, especially during the decision-making process.

Figure 3. Ameroro Dam Project

3.2 Project management information system

The existence of PMIS has significantly improved project management by delivering a more accurate construction process and a better project visualization for construction monitoring. The features available on the PMIS dashboard does not have any specific benchmarks and are developed according to the company's business process needs. The framework in Figure 4 shows the workflow from data collection to processing and output production of PMIS. The primary data such as BIM Model, Digital Survey Data, and Project Data is utilized as the foundation of PMIS dashboard which in this case study is built in the base of a GIS platform, thus geospatial map is becoming the base layer of the information. The production of BIM Model is required and processed with georeferenced coordinate system, inserted to be a raw data for Geo-BIM feature. The Geo-BIM referred to in this paper is the integration of the BIM Model with GIS, hence, to simplify further discussion it will be referred as Geo-BIM. On the other hand, Digital Survey obtained with Photogrammetry methods by using Drone Mapping. This digital surveying operation will produce point clouds and processed into Digital Terrain Model (DTM), Digital Surface Model (DSM), and Orthophoto as a raw data for Geo-BIM. Afterwards, the superimposed BIM Model and Orthophoto in the GIS platform will be beneficial as the progress visualization feature for project monitoring. Moreover, this PMIS dashboard is also equipped with video surveillance from live CCTV that will support the stakeholders for doing construction monitoring remotely. For a better understanding on how PMIS works for the project management process, it will be explained in Figure 4 as shown below.

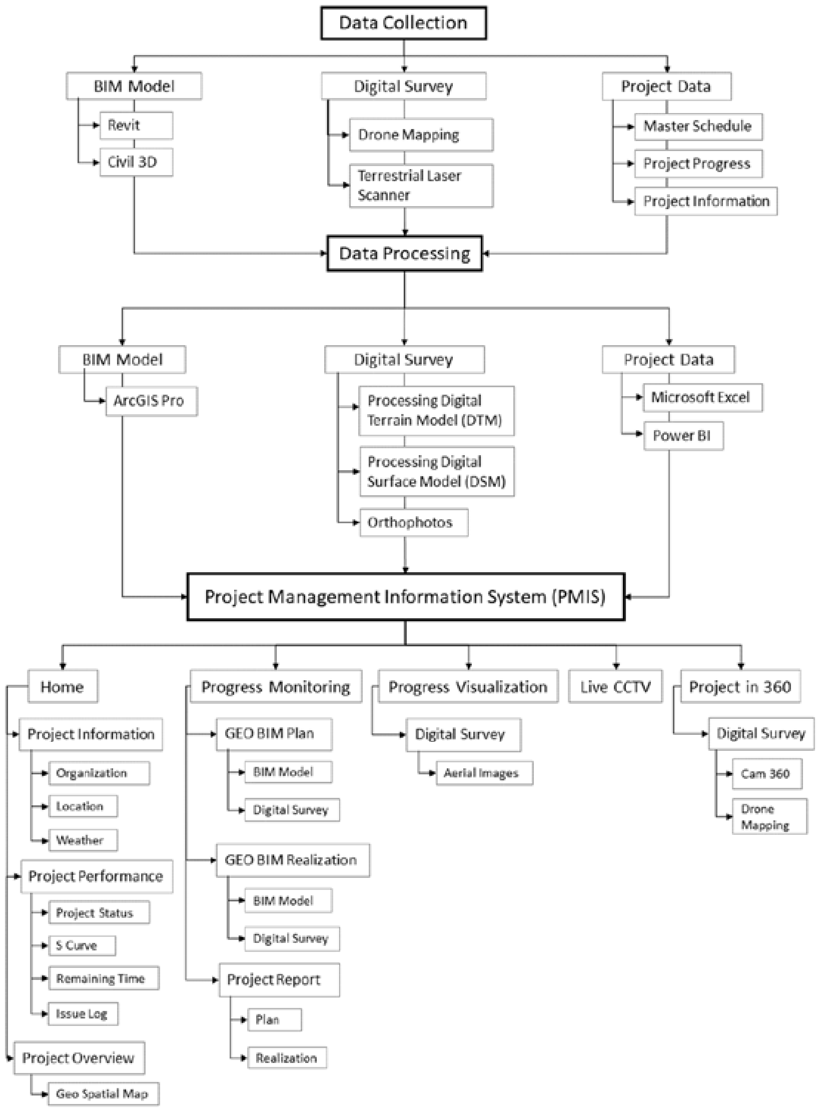

Figure 4. PMIS Flowchart

3.3 Data Collection

As a basis input for PMIS dashboard, data collection is undertaken using two methods namely manual methods with total station and 2-dimensional engineering drawings and digital methods by utilizing digital survey, BIM, and project data. The digital data collection includes Digital Surveying process to obtain the geographic data, real-time data, and making the BIM Model for the visualization and calculation needs.

3.3.1 Manual Data Collection

The conventional method of surveying is undertaken by surveyor using a Total Station Topcon GTS 230 and it took approximately 1,5 hours for 1 hectare. The manual surveying is undertaken by 2-3 surveying engineers. Furthermore, the 2-dimensional engineering drawing usually made at least 1 day for each drawing as shown on Figure 5.

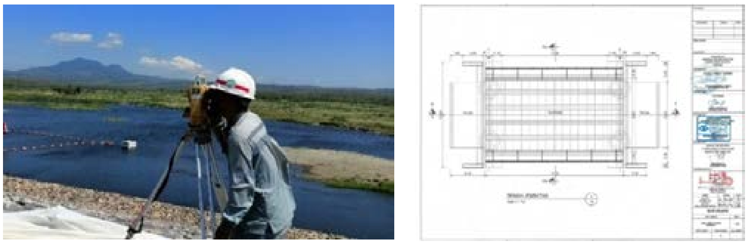

Figure 5. Manual Data Collection with Total Station and 2D Engineering Drawing

3.3.2 PMIS Data Collection

3.3.2.1. Digital Survey

At the earliest stage of the construction, Digital Survey was conducted by BIM Engineer to obtain geographic data to be superimposed with the engineering drawings. The digital surveying process is carried out with Photogrammetry method by using Drone Mapping that will perform aerial surveying and generate a collection of images of the object. The raw data was collected using a drone DJI Phantom 4 Pro V.20 shown in Figure 6. The surveying methods was started by arranging the flying route of the drone and setting up the overlapping rate between each image. Furthermore, Digital Survey method considered effective as it took only 15 minutes approximately for the area of 15 hectares per flight mission with 100 meters of altitude and produced Digital Elevation Model and Orthophotos as the output. This method is conducted regularly, and the data will be embedded on the PMIS dashboard for project monitoring needs.

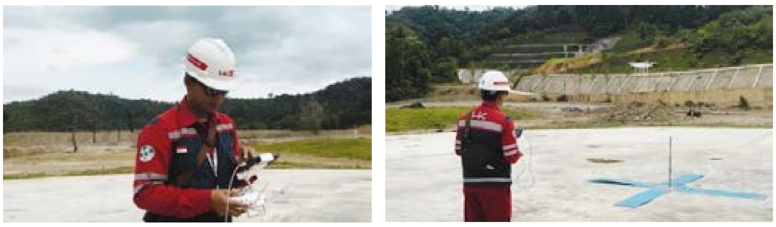

Figure 6. Digital Survey process with Drone Mapping

Figure 7. Photogrammetry Flight Mission

3.3.2.2. Building Information Modelling

During the construction process, Building Information Modelling (BIM) plays an important role as the project visualization. Hence, the BIM Model is an important input data for the PMIS dashboard, which can be later integrated with GIS. The data collection process started with the BIM 3D Model creation based on the detailed engineering drawings using BIM Authoring tools. Afterwards, the coordinate points from the digital survey are inputted on the BIM 3D Model, so that this model has georeferenced data that can be integrated with GIS later on the PMIS Dashboard. The process for generating shop drawings from BIM 3D model only requires 4 hours to finish each drawing. This 3D model is also required to provide the design overview for stakeholders, as well as being the basis for decision-making in solving any clash problems.

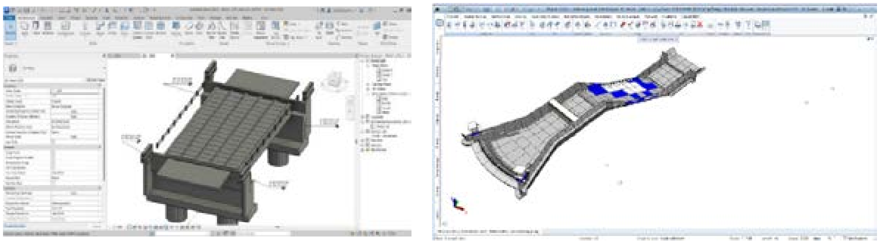

Figure 8. Georeferenced BIM Model

3.3.2.3. Project Data

Besides, the PMIS dashboard also integrated with project data such which compiles stakeholders name, project milestones date, location, and project remaining time to be showed in the project information. Moreover, the PMIS dashboard also integrated with project engineering data such as master schedule, monitoring schedule, 4D scheduling from BIM, plan and realization of project cost that becoming the focal point of the dashboard which will be featured as the project performance.

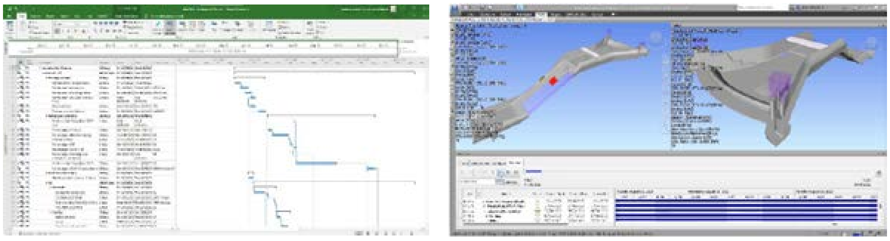

Figure 9. Integrated Project Schedule Data

3.4. Data Processing

3.4.2. Manual Data Processing

For the surveying phase, Total Station obtained RAW data such as distance and elevation level, and the output will be inputted manually on Microsoft Excel and processed in CAD software. Moreover, for the schedule data, the conventional method needs to input manually on Microsoft Excel or Microsoft Project for the monitoring purpose. This process usually requires 6 hours long to produce Cross Section data as a support for Project Monitoring.

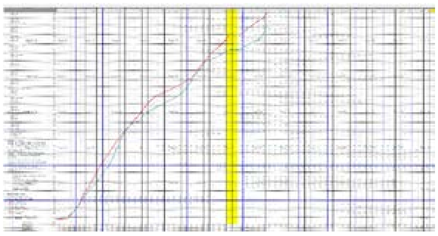

Figure 10. Project Master Schedule

3.4.3. PMIS Data Processing

The graphic visualizations on this dashboard are supported by collaborating platforms and software which data kept in cloud-based or on-premises server. In this case, the company use both, the combination between cloud-based and on premises server because the data is interlinked. Nowadays, digital platforms are build based on collaboration which helps them to grow stronger with the ability on showing other platforms data through open API and interlinked data. As well in this PMIS dashboard, beside using open API to connect the BIM model data, the connector between platforms is developed in spreadsheets that previously arranged with required fields based on each visual requirement. Thus, the information inserted is categorically and historically inputted regarding the visual representation needed in the dashboard then transformed into bar graphs, doughnut graphs or gauge charts.

3.4.4. Project Information

The project information as the basic data, compiles stakeholders name, project milestones date, location, weather condition, and remaining time that becoming the focal point of the dashboard. In the framework of project management, the remaining time shows in countdown to ensure the initial attention of the stakeholders are concerning on how the time and progress are in the right direction, otherwise the rest of information provided in this dashboard will be able to support the necessary decision making to guarantee the timely delivery of the project.

Figure 11. Project Information Data Processing

3.4.5. Project Performance

Project Performance is used to determine if a project is in the Excellent, Warning, or Critical category based on the actual and anticipated project cost value, income realization, and plan. The Project Performance contains many information and integrated with the project engineering data such as master schedule, monitoring schedule, plan, and realization of project cost. Firstly, these databases are inputted in Microsoft Excel and processed on ArcGIS Pro. Then the dashboard is created on ArcGIS Dashboard Enterprise, and these S curve dashboards are inputted in PMIS dashboard through the ArcGIS Experience Builder.

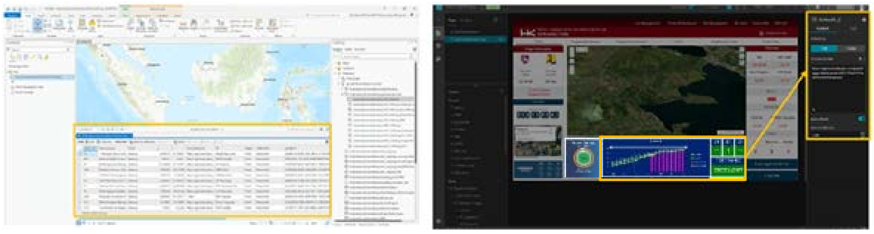

Figure 12. Project Performance Data Processing

3.4.6. Geo-BIM

During the data processing, the Digital Survey data which obtained from Drone Mapping will be processed to be superimposed with the BIM 3D Model. The output produced from the drone mapping were subsequently translated into Orthophoto and Digital Elevation Model (DEM) to be processed in Agisoft metashape. Afterwards, DEM can produce 2 outputs, namely Digital Terrain Modelling (DTM) and Digital Surface Modelling (DSM). DTM could be processed as a contour and can be developed as cross section and top surface in Autocad Civil 3D to produce cut and fill volume calculation for progress monitoring. Meanwhile the DSM or Digital Survey Modelling will be processed as 3D Object. The 3D object will be inputted in ArcGIS and overlayed with the BIM Model to see the construction progress, as shown on Figure 13 and 14.

Figure 13. Orthophoto Data Processing

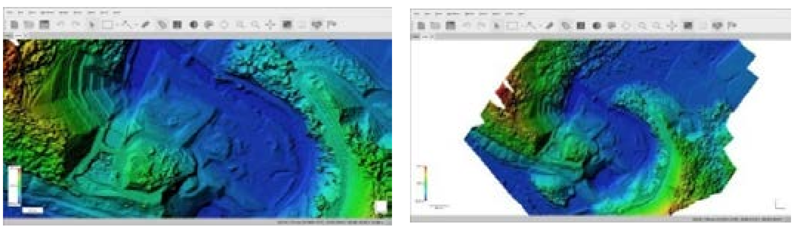

Figure 14. Digital Elevation Model (DEM) Data Processing

3.5. Result and Discussion

After the data processing, many outputs showcased as the result of PMIS. The final output contains project performance, Geo-BIM, and Live CCTV which beneficial as the progress visualization and enhance the decision-makings during the construction progress. This dashboard usually used as project management plan by project stakeholders namely project manager, site engineer manager, engineers, and head-office management team to identify the current project status and regular monitoring purposes during the coordination meeting.

3.5.2. Project Performance

The main page of PMIS dashboard allows us to identify the current project status and project performance. It includes the project information such as project value and time of completion, project remaining time, project location, and the weather. The project performance feature also integrated with the project master schedule, showcasing the S Curve of the project progress. Moreover, it completed with the Schedule Performance Index (SPI), Cost Performance Index (CPI), and Efficiency Performance Index (EPI) which will resulting as the project performance conclusion, as shown on Table 1. Moreover, it also completed with the project data such as financial data, QHSSE data, Issue log and action plan.

Table 1. Project Performance Formula

	SPI	EPI	CPI
EXCELLENT	>1	>1	>1
WARNING	>1	<1	<1
CRITICAL	<1	<1	<1

SPI = Schedule Performance Index

EPI = Efficiency Performance Index

CPI = Cost Performance Index

This formula is referred as Project Forecasting, that is utilized as a monitoring tool that ease the project management team to identify risks and take actions, as well as allocate the resources early. The result can be seen on the PMIS main dashboard which aims to increase the project team's awareness of current project status as shown on Figure 15.

Figure 15. Project Performance

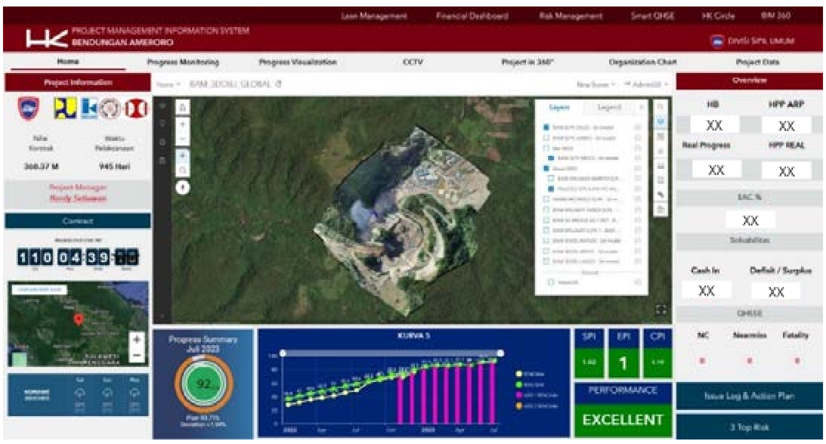

Figure 16. Ameroro Dam Project Performance on PMIS Dashboard

3.5.3. Progress Visualization

The aerial images produced from the Drone Mapping are shown in Progress Visualization feature as an overview of the construction progress. This feature is beneficial for regular monitoring purposes to ensure many points on the site that are difficult to reach manually, so that if there are any construction issues such as initial cracks occur, it can be detected and anticipated immediately.

Figure 17. Progress Visualization

3.5.4. Progress Monitoring with Geo-BIM

As a result of the integration between BIM 3D Model and digital data, Geo-BIM was obtained as one of the features of PMIS. In addition, the results from digital survey namely geospatial data, orthophoto, and 3D objects can be superimposed with the BIM Models and site progress data to be integrated in PMIS as digital twin to the existing conformance to the plan accurately with the appropriate coordinates as shown in Figure 18. Moreover, this feature also enables us to make a comparison between the planned construction action plan on the current month versus the realization of construction action plan, which both visualized in BIM overlayed with orthophoto. Manual methods monitoring can only use ms project in terms of scheduling and cannot provide overlay visualization data. Meanwhile, the progress monitoring using PMIS provides Geo-BIM that combined with the project schedule, that can be created for weekly action plan. Each realization progress will be inputted into the Geo-BIM as overlayed data. Then the result of this sumperimposed data can be compared for regular monthly monitoring to identify the deviations. Therefore, if there is any deviations, a strategy can be made to catch up the project schedule. Hence, the integration between photogrammetry with BIM Model accelerates the construction monitoring process as well as making the action plan with the help of the digital twin as the project visualization. Thus, this integration assists stakeholders on decision makings more accurately and quickly.

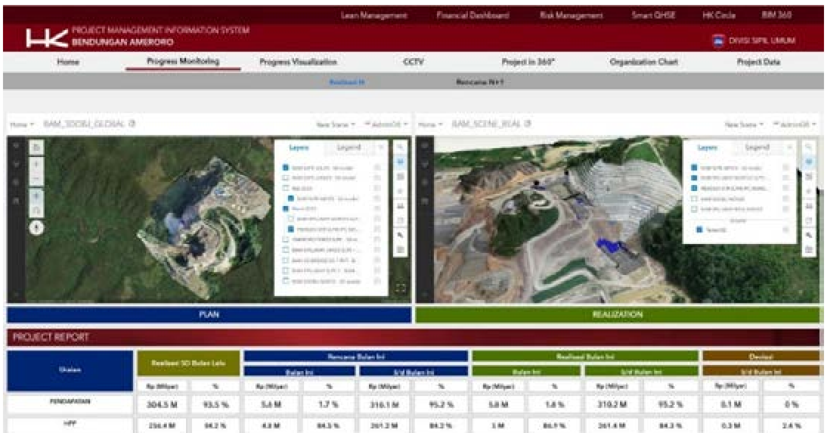

Figure 18. Progress Monitoring with Geo-BIM

3.5.5. Live CCTV

There is a Live CCTV feature which integrated with site project cctv support the progress monitoring purposes. Moreover, this Live CCTV feature enable the stakeholders to do real-time monitoring remotely during the construction process. The CCTV units are strategically placed in the production and construction areas, showing not only the current activities but also assisting safety manager to ensure accident prevention with real time monitoring from the control room.

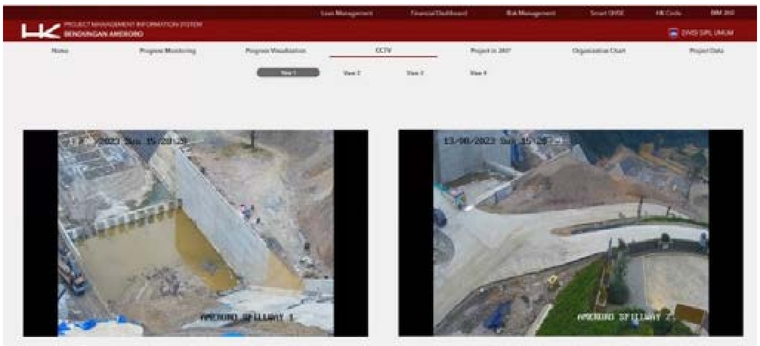

Figure 19. Live CCTV

3.5.6. Comparative Analysis

As we can see from the data above, the manual methods of project monitoring require a lot of time and manhour, rather than the digital monitoring through the PMIS. The comparative analysis below is affected by many factors. On the quantitative side, it affected by manpower and manhour needed during the data collection and processing, with formula as illustrated below:

Data Collection Time Productivity Rate for every 1 hectare

$$Productivity\ Rate = \left|\frac{\sum Manual\ Survey\ time\ (min)}{\sum Digital\ Survey\ time\ (min)}\right|$$

$$Productivity\ Rate = \left|\frac{90\ \ min}{1{,}5\ \ min}\right| = \boldsymbol{60x}$$

Data Collection Manpower Efficiency

$$Efficiency\ Rate = \left|\frac{\sum Manual -\ Digital\ Survey\ manpower\ (people)}{\sum Manual\ Survey\ manpower\ (people)}\right| x\ 100\%$$

$$Efficiency\ Rate = \left|\frac{(3-2)\ peoples}{3\ peoples}\right| x\ 100\% = \mathbf{33}\%$$

Data Processing Time Efficiency

$$Efficiency\ Rate = \left|\frac{\sum Ms\ Project + BIM\ (hours)}{\sum Ms\ Project\ (hours)}\right| x\ 100\%$$

$$Efficiency\ Rate = \left|\frac{8\ hours}{16\ hours}\right| x\ 100\% = \mathbf{50}\%$$

Data Processing Productivity Rate

$$Productivity\ Rate = \left|\frac{\sum 2D\ Drawings\ time\ (hours)}{\sum BIM\ Drawings\ time\ (hours)}\right|$$

$$Productivity\ Rate = \left|\frac{8\ hours}{4\ hours}\right| = \boldsymbol{2x}$$

On the other side, the utilization of PMIS also shows significant difference in terms of output quality, especially to support the project monitoring and decision-makings as shown on table 2.

Table 2. Comparative Result of Project Management between using PMIS and non-PMIS

Factors	Project Management without PMIS	Project Management using PMIS
Data Collection	Consisted of single-sourced data. The process requires longer time to collect data from many involved parties	Consisted of integrated data, which more comprehensive between time and visualization. The data automatically updated by the Engineer with a faster time.
Project Monitoring	Manual monitoring requires longer time and cannot be schedule-based since the realization progress from the surveying data is not integrated.	Project Monitoring with PMIS allows the integration between GIS, BIM, and Project Schedule to be superimposed into monthly overlayed data for regular monitoring purpose
Building Information Modelling	It is unintegrated with the geospatial data so clash detection with the site cannot be checked	It can be overlayed with the digital survey data to see the conformance with the existing site as well as beneficial for progress monitoring
Project Performance	The management team in project or headquarter may be unaware with project current status by the unavailability of updated project performance data	Increase the management team awareness of project current status and beneficial to make a corrective action plan
Decision Makings	Requires a longer time by the unintegrated and less updated data and the absence of visualization,	The availability of updated project data and visualization provide more reliable data and fasten the decision-makings
Historical Data	The engineering data are unintegrated and may be lost after the project finished	The historical engineering data are stored and integrated in one platform
Limitation	Requires longer time	Highly dependent to online internet network

4. CONCLUSIONS

The presence of PMIS as a Digital Twin plays a crucial role during the project monitoring in ensuring the timely delivery of a construction phase of a project. It can be concluded from the results above; the quantitative data shows the digital monitoring is more effective than conventional monitoring during the data collection process. In terms of time, digital monitoring improves the productivity by 60x faster than the manual method, with manpower efficiency of 33%. Moreover, the implementation of BIM improves the productivity up to 2x faster than the conventional methods and cut the time efficiency by 50%. From the qualitative side, PMIS consisted of integrated data which more comprehensive between time and visualization, rather than without PMIS that consisted of single-sourced data. In terms of the output quality, the integration of BIM and GIS provide more reliable data to support the decision makings by the presence of updated project data and visualization, that can be overlayed with the digital survey data. Moreover, the project performance feature increase awareness of project current status that ease the project management team to identify risks, take actions, and make the corrective action plan. PMIS is going to be a major difference in asset management aspect, with the collected database from construction phase have been prepared to be handed over to the asset manager as the reference for maintenance activities. Meanwhile with the conventional methods, unintegrated engineering data are subjected to be scattered after the project finished. Therefore, it can be concluded that the utilization of PMIS accelerates stakeholders' decision through data driven decision making while reduce and mitigate risk of cost overruns as early as possible with the findings on project monitoring. Future recommendation of the historical project data which collected in PMIS is expected for future project management plan, especially for project with the same characteristic. Besides, the PMIS utilization is improving collaboration and understanding of the project situation through Digital Twin with the data intensive communication and eliminate the inefficient process with remote monitoring. All in all, the digital twin technology nowadays has shown a significant role on providing the efficiency and optimizing the productivity on construction industry where each stakeholder should spot the benefit for their organization. Likewise, in Hutama Karya, PMIS capabilities currently in use are highly adaptable to future development and updating according to organizational needs and technological advancement. Hence, not only the tools are evolving but also the people need to be agile and adaptive to maintain its effectiveness to support company's business process excellence.

5. ACKNOWLEDGEMENTS

A grateful acknowledgment is delivered to PT Hutama Karya (Persero) and Ameroro Dam Project as the fund and research support for the PMIS dashboard as a Digita Twin reesarch. The continuous support from the company's management has driven to many improvements and development to the research and the use of the PMIS dashboard in supporting the project management for all the companies' projects around Indonesia.

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HUMAN-IN-THE-LOOP DIGITAL TWIN FRAMEWORK FOR ASSESSING ERGONOMIC IMPLICATIONS OF EXOSKELETONS

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ABSTRACT: *Exoskeletons are increasingly being recognized as ergonomic solutions for work-related musculoskeletal disorders in the construction industry. However, users of active back-support exoskeletons are susceptible to various physical and psychological risks, which could be exoskeleton type-or task-dependent. A test bed is needed to enable deployment and assessment of risks associated with exoskeleton-use for construction tasks. This study aims to develop a human-in-the-loop digital twin framework for assessing ergonomic risks associated with the use of active back-support exoskeletons for construction work. A literature review was conducted to identify risks associated with exoskeletons and the technologies for quantifying the risks. This informed the development of a system architecture describing the enabling technologies and their roles in assessing risks associated with active back-support exoskeletons. Semi-structured interviews were conducted to identify construction tasks that are most suitable for active back-support exoskeletons. Based on the identified tasks, a laboratory experiment was conducted to quantify the risks associated with the use of a commercially available active back-support exoskeleton for carpentry framing tasks. The efficacy of the digital twin framework is demonstrated with an example of the classification of exertion levels due to exoskeleton-use using a 1D-convolutional neural network. The study showcases the potential of digital twins for comprehensive ergonomic assessment, enabling stakeholders to proactively address ergonomic risks and optimize the use of exoskeletons in the construction industry. The framework demonstrates the significance of evidence-based decision-making in enhancing workforce health and safety.*

KEYWORDS: *Digital twin, ergonomics, exertion, exoskeletons, risk assessment, sensing technologies, work-related musculoskeletal disorders.*

1. INTRODUCTION

The United States Bureau of Labor and Statistics reports that the construction workforce continues to experience a higher rate of work-related musculoskeletal disorders compared with workers in other industry sectors combined. The back is one of the most affected body parts. Back-related injuries account for about 43% of all work-related musculoskeletal disorders (BLS, 2023). Exoskeletons are emerging as potential solutions to WMSDs. Specifically, active back-support exoskeletons, a class of exoskeletons, have been shown to reduce the risks of overexertion which is one of the triggers of back-related injuries. For example, studies have revealed a reduction in muscle activity (Theurel et al., 2018), discomfort in the body parts (Gonsalves et al., 2021; Kim et al., 2019), rate of exertion (Alemi et al., 2020; Baltrusch et al., 2021), and range of motion (Cumplido-Trasmonte et al., 2023) due to exoskeleton-use. These benefits are motivating construction contractors to explore active back-support exoskeletons for construction work. However, studies have also mentioned that exoskeleton-use on construction sites could trigger unintended consequences such as loss of balance or fall risks (Alabdulkarim et al., 2019; Kim et al., 2019; Massardi et al., 2023), physical discomfort and pain (Gonsalves et al., 2023; Gonsalves et al., 2021), fatigue (Theurel et al., 2018), and restricting movement when climbing ladders (de Looze et al., 2016; Kim et al., 2019). These highlight the likely task-specificity of exoskeletons. In addition, the unintended consequences could also be specific to exoskeleton types (Fox et al., 2020; Kim et al., 2019). With the increase in commercially available exoskeleton solutions, a testbed would be beneficial to support the testing and assessment of the solutions for construction tasks. This has downstream implications for enabling real-time monitoring of exoskeleton-use during construction, which could inform strategies for reducing unintended risks.

Sensing technologies provide opportunities to measure risks associated with exoskeleton-use (Akanmu et al., 2020; Ogunseiju et al., 2021). Data from sensing technologies could be modeled and analyzed to extract insights that can be mapped to workers' virtual replicas and controls (e.g., rating meters). This digital representation could be used by stakeholders (e.g., project and safety managers, and manufacturers) to develop control strategies such as deciding on the contextual use of exoskeletons (i.e., most suitable application tasks and duration of use), suitable exoskeleton types, and modifications to exoskeleton design. This digital representation is referred to as the human-in-the-loop digital twin which is a two-way symbiotic relationship between physical entities (e.g., workers and exoskeleton) and their virtual representative in which humans initiate the control (N. Zhang et al., 2022). The implication is that the ergonomic consequences of workers' postures while using exoskeletons can be obtained in real-time which can enhance their ability to control or self-manage their exposures (Ogunseiju et al., 2021). Thus, this paper presents a digital twin framework for assessing the risks associated with exoskeleton-use for construction work. A review of the literature was conducted to identify risks associated with exoskeleton-use and

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Abiola Akanmu, Adedeji Afolabi, Akinwale Okunola, *Human-in-the-Loop Digital Twin Framework for Assessing Ergonomic Implications of Exoskeletons,* pp. 1233-1244, DOI 10.36253/979-12-215-0289-3.121

the sensing technologies for quantifying the risks. The risks enabled the development of a system architecture to support the development of a human-in-the-loop DT framework that can inform decisions to support the sustainable use of exoskeletons in construction. Construction workers are interviewed to identify tasks that would benefit from active back-support exoskeletons. The efficacy of the DT framework is demonstrated with an example of predicting risk of exertion due to the use of an active back-support exoskeleton for one of the tasks. This study motivates discourse on human-in-the-loop Digital Twins for construction applications. The study highlights the extent to which physiological risks associated with exoskeleton-use can be predicted.

2. BACKGROUND

2.1 Exoskeletons for Construction Work: Risk and Assessment Techniques

Studies have shown that exoskeletons have intended benefits and unintended consequences. For instance, exoskeletons are prospective innovative ergonomic interventions aimed at reducing overexertion in various parts of the body (Gonsalves et al., 2021). This may in turn reduce the occurrence of WMSDs among construction workers (Akanmu et al., 2020). There is evidence that exoskeletons can reduce back muscle activities by 23 - 35% (Abdoli-e and Stevenson, 2008). Other benefits revealed in the literature include reduced discomfort to the body parts (Alemi et al., 2020), increased productivity, financial gains, and work retention (Kim et al., 2019), and increased ability to lift heavier loads and perform repetitive tasks (Mahmud et al., 2022). Despite these benefits, there are some unintended consequences associated with exoskeletons. Exoskeletons have been known to trigger risks broadly classified in Table 1 as physical and psychological risks. The physical risks include joint hyperextension, instability and fall risk, muscle fatigue, bruising, skin and soft tissue injury, and increased cardiovascular demand and metabolic cost (Howard et al., 2020; Massardi et al., 2023; Theurel et al., 2018). For example, skin irritation or chemical burns could occur if an exoskeleton battery leaks corrosive materials to the user (Howard et al., 2020). In addition, due to the added weight of the exoskeleton, the user's center of gravity may be significantly impacted causing balance problems and a diminished recovery rate (Alabdulkarim et al., 2019). Gonsalves et al. (2021) showed that exoskeletons result in discomfort in the chest and thigh regions. Previous research has indicated that exoskeletons can redirect loading from one part of the body to another (Picchiotti et al., 2019). For example, during overhead work, exoskeletons reduce the muscle activity in the shoulder and the back of the arm but increase muscle activity in the lower back, abdomen, and legs (Theurel et al., 2018). Besides, usability, self-efficacy, and safety could be negatively impacted because the exoskeletons could get caught around wires and may affect work postures (Baltrusch et al., 2021). Exoskeletons are sometimes incompatible with some personal protective equipment such as safety harnesses (Gonsalves et al., 2023). Previous studies (Omoniyi et al., 2020; Siedl et al., 2021) have also identified psychological risks such as decreased situation awareness/distraction, cognitive overload, fear of the device, and overconfidence in the device. Various sensing technologies, such as inertial measurement units and electromyographs, have been employed to quantify these risks. Similarly, objective measures from the sensing technologies have been validated with subjective assessment instruments such as the NASA Task Load Index and Berg Balance Scale. These are highlighted in Table 1.

Table 1: Risks and assessment techniques of exoskeletons.

Categories of risks	Risks	Objective Assessment	Subjective Assessment	Related Studies
Physical risks	Joint hyperextension	Inertial measurement units; Cameras	Local Perceived Pressure scale; Borg Rating of Perceived Exertion scale	(Theurel et al., 2018)
	Instability and Fall risk	Pressure insoles; Force plates	Berg Balance Scale	(Alabdulkarim et al., 2019; Kim et al., 2019; Massardi et al., 2023)
	Muscle fatigue	Electromyography	Borg Rate of Perceived Pain Scale; Borg Rate of Perceived Exertion Scale	(Theurel et al., 2018)
	Hygiene issues/Bruising, Skin and soft tissue injury	Biocompatibility tests	Usability questionnaires e.g., System Usability Scale	(Howard et al., 2020; Massardi et al., 2023)
	Cardiovascular demand	Electrocardiogram; Photoplethysmogram	Workload assessment questionnaires e.g., NASA Task Load Index (TLX)	(Moyon et al., 2018; Theurel et al., 2018)
	Metabolic cost risk	Indirect calorimetry	Questionnaires for workload assessment (e.g., NASA TLX), Rating perceived exertion (RPE) with the Borg Category Ratio (Borg CR-10)	(Alemi et al., 2020; Baltrusch et al., 2021)

	Usability of the device (e.g., perceived discomfort, chest pain, catch and snag risks)	Eye tracker; Electromyography	Focus groups; Usability questionnaires; Borg CR 10 scale; Body part discomfort scale	(Gonsalves et al., 2021; Kim et al., 2019; Ogunseiju et al., 2022)
Psychological risks	Decreased situation awareness/ Distraction	Eye tracker	NASA-TLX	(de Looze et al., 2016; Delgado et al., 2020)
	Exertion	Electrodermal activity sensor	Rating perceived exertion (RPE) with the Borg Category Ratio (Borg CR-10)	(Man et al., 2022; Theurel et al., 2018)
	Fear; Lack of trust	Electromyography; Photoplethysmogram; Electrodermal activity sensor	Interview; Self-developed questionnaires; subjective psychological impact test	(Omoniyi et al., 2020; Upasani et al., 2019)
	Cognitive overload	Electroencephalography; Eye tracker; Electrodermal activity sensor	NASA-TLX; MF (M-VAS) and boredom (B-VAS)	(Cumplido-Trasmonte et al., 2023)
	Overconfidence effect	Camera Videos; Optical tracking system (OTS)	Focus groups; Questionnaires (e.g., Modified Spinal Function Sort)	(Baltrusch et al., 2021; Siedl et al., 2021)

2.2 Digital Twin for Ergonomic Risk Assessment

In recent years, there have been increasing explorations of DT for diverse applications including workforce health and safety. Sharotry et al. (2022) developed a DT to track the biomechanical fatigue in operators caused by repetitive action in lifting activities. The study analysed changes in the joint angles in workers' body joints using a dynamic time-warping algorithm. Another study (Greco et al., 2020) presented an ergonomic risk mapping of DT workstations using a wearable motion capture system and inputting in virtual simulated environments. With the DT, the authors were able to identify risk indexes related to working postures, exerted forces, material manual handling and repetitive actions, and sources of biomechanical overload. In construction, Ogunseiju et al. (2021) developed a DT framework for improving self-management of ergonomic risks. However, scarce studies have explored the assessment of exoskeleton-use using a DT environment. Furthermore, Greco et al. (2020) opined that existing DT frameworks have limited roles for users or stakeholders. Humans play vital roles in workplace systems; therefore, supporting technologies should be designed to facilitate their input (Sharotry et al., 2020).

3. METHODOLOGY

The approach employed in conducting this study is shown in Figure 1. First, a review of the risks associated with exoskeletons and the technologies for measuring the impact of the risks was conducted (Section 2.1). This informed the development of an architecture of a human-in-the-loop DT system for assessing risks associated with active BSEs. Semi-structured interviews were conducted to identify construction tasks that would benefit from the use of active BSEs. A laboratory experiment was conducted to quantify the risks associated with using active BSEs. This informed the development of an example of a DT-based model for assessing the risk levels of exertion during exoskeleton-use. These are described as follows:

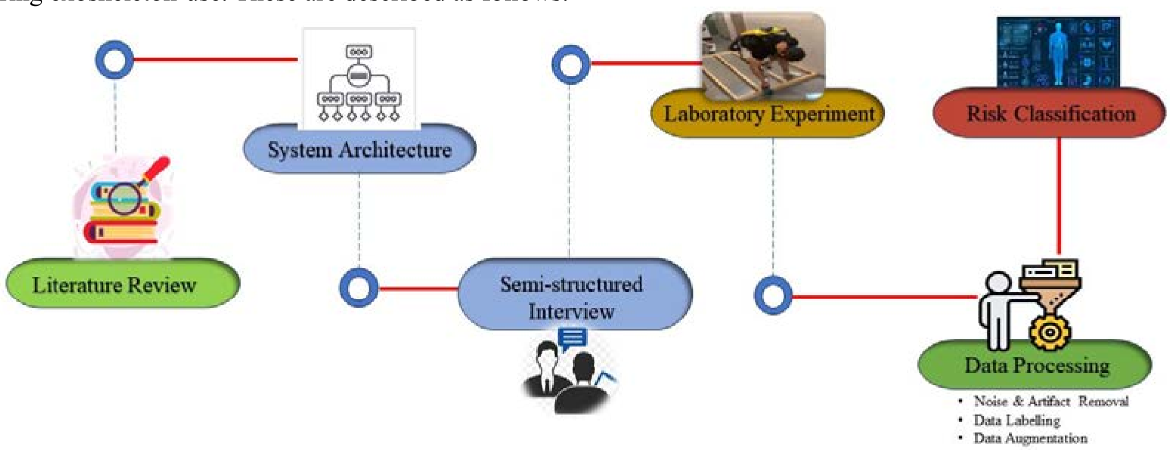

Fig. 1: Overview of research methodology.

3.1 System Architecture

The system architecture shown in Figure 2 is built to illustrate the proposed human-in-the-loop DT framework. The system architecture shows the enabling technologies and their role in supporting the assessment of ergonomic risks associated with exoskeleton-use. The architecture comprises six layers include physical layer, data layer, data transmission layer, storage layer, application layer, and access layer. These are described as follows:

3.1.1 Physical layer

The physical layer comprises sensing technologies and physical devices. The sensing technologies support capturing of physical and psychological risks, and environmental characteristics of work areas. The physical risks include local muscle fatigue, fall risk, joint hyperextension, and metabolic risk which can be measured using electromyography (EMG), pressure insole, inertia measurement unit (e.g., comprising of accelerometers, gyroscope, and magnetometer), and calorimeter respectively. The psychological risks include cognitive overload, lack of trust, and decreased vigilance which are measured using an electroencephalogram, electrocardiogram, photoplethysmogram, and eye tracker respectively. The workspace or site conditions can be captured using environmental sensors such as temperature and humidity sensors and image-based sensors such as cameras and laser scanners. Physical devices include reality technologies such as virtual and augmented reality devices, and other data acquisition technologies for collecting subjective data to evaluate the aforementioned objective measures. Reality technologies support the development of risk-free simulated construction site environments where workers can practice work with different exoskeletons.

3.1.2 Data layer

Data from the physical layer are captured in the data layer. The data layer contains the data generated from the sensors and physical devices, such as raw acceleration and angular velocity from the IMU, brain waves from EEG, electrical conductance of the skin from EDA sensors, eye fixations from eye trackers, muscle activity from EMG, and temperature and humidity from temperature and humidity sensors. Subjective data (such as perceived cognitive load, rate of exertion, and discomfort levels) are also stored in the data layer. This layer also contains videos of construction work and general characteristics of the work area that might explain or influence risk factors of WMSDs.

3.1.3 Data transmission layer

The data transmission layer transfers data from the data layer to other layers for storing, modeling and analysis, and DT representation. Different communication technologies could be used in this layer, such as short-range transmission technologies e.g., Wi-Fi, Bluetooth, Zigbee, near-field communication (NFC), and Zwave, and long-range transmission technologies e.g., 3G, 4G long-term evolution (LTE), and low-power wide-area networks.

3.1.4 Storage layer

This layer consists of cloud services that store data received from the data transmission layer and application layer. Heterogenous data from these layers are gathered and stored in a cloud storage system for exchange or sharing with other layers. The data or information can be beneficial for extracting other insights that can help improve the health and safety of workers. Depending on the stakeholders and their information needs, multiple repositories may be included. As such, different access rights may be provided. For instance, a data analyst may need access to label subjective data obtained from the data layer to enable assessments involving risk classifications. A safety/health manager may be provided access to data that can inform impact on workers' health while impacts while a project manager may be provided access to data relating to impact on productivity.

3.1.5 Application layer

This layer includes algorithms and applications for processing and analyzing data obtained from the storage layer. The data are processed and represented in formats that can be used by decision-makers in the access layer (Section 3.1.6) for decision-making. For example, to assess workers' levels of exertion from their electrodermal activity (EDA) signals, this layer will use signal processing algorithms, feature extraction, and deep learning networks (e.g., conditional generative adversarial network, recurrent neural network, and long short-term memory), and visualization algorithms. Signal processing algorithms such as discrete wavelet transforms and adaptive predictor filtering methods will be used to reduce artifacts from the EDA signals. A symmetric multilayer perception model for extracting features will be used to extract informative features from the EDA signals. The extracted features will be fed into deep learning networks (e.g., conditional generative adversarial network, recurrent neural network, and long short-term memory) to classify the EDA signals into the levels of exertion. Finally, visualization algorithms will be used to augment the levels of exertion on a virtual replica of the worker and a rating meter.

3.1.6 Access layer

In the access layer, stakeholders can visualize the impact or extent of the risks as a virtual replica of the worker and a rating meter. This layer includes the following: (1) beneficiaries of the DT platform and (2) how they access the DT platform. The beneficiaries may include safety managers, project supervisors, and product manufacturers. Safety managers may want to understand if the workers are reaping the intended health benefits of the technology. Project supervisors may want to know the impact of the technology on project performance. Both stakeholders could use the feedback to work with manufacturers to plan more suitable designs for their projects. The stakeholders can monitor the performance of the workers via interactive dashboards and web applications. The performance of the workers will be shown in the form of their virtual replica and a rating meter to interpret the risks. For example, the levels of exertion associated with an exoskeleton (e.g., no exertion, low exertion, medium exertion, and high risk) that is computed in the application layer, will be shown as different colors in a virtual replica and rating meter (e.g., green, yellow, and red human). In this way, the project stakeholders can understand the type and extent of the risk, which could inform decision making such as which type of exoskeleton to use for what task, how long the exoskeleton should be used for the task, and changes that should be made to the device to better adapt it to construction work.

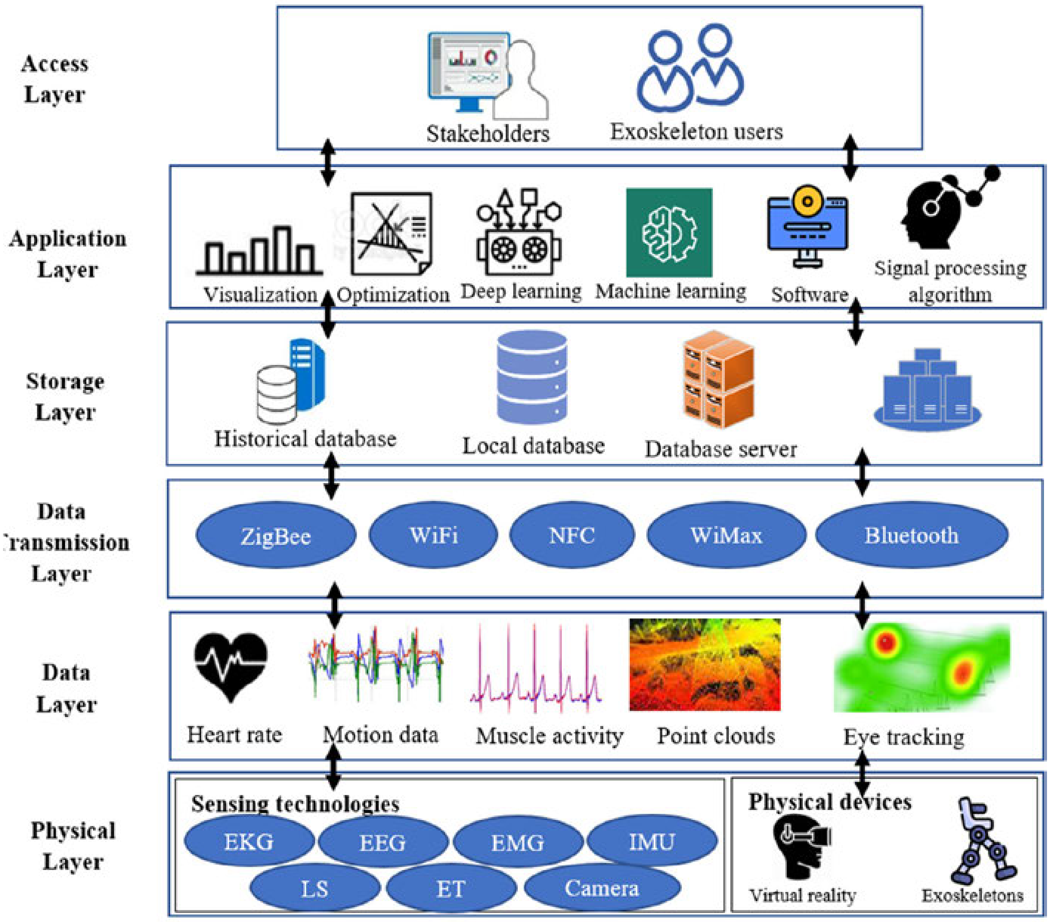

Fig. 2: System architecture.

3.2 Semi-Structured Interview

Semi-structured interviews were conducted with industry practitioners (n=8) to understand the construction tasks that would benefit from the use of active back-support exoskeletons. A purposive sample was used to identify and select potential participants who could provide valuable insights to the study. The research team selected participants with experience in construction safety, and technology implementation in the construction industry. The interviews were conducted over Zoom and recorded. The transcripts of the interview were coded and emerging themes were identified. An inter-coder reliability test was conducted on the coded data using the Cohen-Kappa coefficient. Cohen-kappa coefficient of 0.90, indicating a strong level of agreement, resulted from the assessment.

3.3 Experimental Procedure, Participants, and Data Collection

Sixteen students were recruited to participate in a carpentry framing activity; one of the activities identified from Section 3.2 as beneficiaries of active back-support exoskeletons. The participants reported no prior issues related to musculoskeletal disorders that could affect their performance in the study. The experiment was approved by the Virginia Tech Institutional Regulation Board (IRB: 19-796). The task involved the following: (1) measuring timber planks (i.e., four 1”x4”x47” planks and two 1”x4”x70” planks) needed to construct a 47”x70” frame; (2) assembling the measured timber materials as shown in Figure 3; (3) nailing the assembled timber frame using a nail gun; (4) lifting and moving the erected frame, which weighs approximately about 40lbs, to an upper floor via staircase for installation on the upper floor; and (5) installing the frame by aligning the frame with an existing wall. The participants completed these tasks while wearing CrayX, an active back-support exoskeleton from German Bionics. Their electrodermal activity was measured using Emotibit, an open-source biosensor. The data was collected at 50Hz i.e., 50 data points per second. After performing the framing task, each participant was presented with Borg’s rating of exertion scale (Borg CR-20) and asked to provide subjective ratings of their perceived exertion for the entire task. The Borg scale ranges from 6 (not exhausting) to 20 (extremely exhausting) (Albert et al., 2021; Borg, 1982). The participants’ ratings of perceived exertion were measured using the Borg’s exertion rating scale (Borg CR-20) which ranges from 6 to 20, where 6 represents no exertion and 20 represents maximum exertion. Figure 3 shows participants performing framing tasks with the exoskeleton and the biosensor. The task was video recorded.

Fig. 3: Participant performing framing task while wearing an exoskeleton and EEG cap.

3.4 Data Preprocessing

3.4.1 Noise and artifact removal

The collected EDA signals were filtered to remove the noise and artifacts. A low pass filter with a cut-off frequency of 4 Hz was employed to remove the noise. A Gaussian filter was used to smoothen and attenuate the artifacts. MATLAB was used for this purpose.

3.4.2 Data labeling

Using the time-stamped video, EDA data corresponding to each participant’s tasks were sorted and structured. The ratings of 7– 11, 12 – 14, and 15 – 20 were represented as low exertion, medium exertion, and high exertion, respectively (Chowdhury et al., 2019). The sorted EDA data of each participant was labeled based on their intensity class as shown in Table 2.

Table 2: Classes, labels, and data points.

Classes	Labels	Percentages of participants (%)	Number of data points
Low Exertion	LE	70	50759
Medium Exertion	ME	12	6823
High Exertion	HE	18	14072

3.4.3 Data augmentation

The EDA data of the minority classes were augmented due to the imbalanced nature of the datasets. Studies have shown that balanced datasets result in the Synthetic Minority Oversampling Technique (SMOTE) being employed to balance the EEG data of the minority classes with the majority classes (Sowjanya & Mrudula, 2023). For example, from Table 2, the ratio of the datasets in the LE, ME, and HE classes (i.e., Low Exertion, Medium

Exertion and High Exertion respectively) is 7:1:4. As shown in Table 3, more datasets were generated with SMOTE to balance the datasets of the minority classes (i.e., Medium Exertion and High Exertion) with the class with the most datasets (i.e., Low Exertion).

Table 3: Classes, labels, and data points (raw and balanced).

Classes	Labels	Number of raw data points	Number of balanced data points
Low Exertion	LE	50759	50759
Medium Exertion	ME	6823	50759
High Exertion	HE	14072	50759

3.5 Risk Classification

This study employs a 1-D convolutional neural network to classify the EDA data into the above-mentioned classes (i.e., LE, ME, and HE). 1-D CNN is suitable for 1D signals whose applications have high signal variations (Y. Zhang et al., 2022). The network comprises an input layer, a convolution 1-D layer, a batch normalization layer, a Rectified Linear Unit (ReLU) layer, a dropout layer, a maxpooling layer, a fully connected layer, a softmax layer, and a classification layer. The convolution layer applies filters to the input data obtained from the input layer and extracts distinctive features using 10 filters of width 10. The batch-normalization layer improves the stability and speed of training the network by normalizing the input to each layer. The ReLU layer applies a non-linear activation function to the output of the batch-normalization layer. The dropout layer helps to prevent overfitting of the model. The maxpooling layer down-samples the output of the dropout layer. In the fully connected layer, a linear transformation is applied to the input vector through a weight matrix so that every input influences every output of the output vector. The softmax layer takes in the output from the previous layer and presents a vector that illustrates the probability of the class that the input belongs to. The classification layer presents the results of the softmax layers as classes of the assessed risks. The network was trained using the Adam optimizer (Karim et al., 2019). Due to the size of the dataset, 300 epochs were used. The learning rate was set to 0.01.

The balanced data was split as follows: 70% of the data was set aside for training, 15% of the data was also set aside for validation and 15% was intended for testing the trained model. MATLAB R2023a, installed on a machine with NVIDIA GeForce RTX 2080 GPU and 16GB memory, was employed for the classification. Commonly used metrics for assessing the performance of machine learning models were employed in this study. These include accuracy, precision, recall, and F1-score (Bangaru et al., 2021).

4. RESULTS AND DISCUSSION

4.1 Construction Tasks for Active Back-Support Exoskeleton-Use

The results of the semi-structured interview were represented in the form of a word cloud. Word clouds are graphical representations of the frequency of concepts or keywords that are significant in discourses (Adu, 2019). The word cloud in Figure 4 provides a quantitative and visualized method to illustrate the key construction tasks suggested by the participants to benefit most from active back-support exoskeletons. The most mentioned tasks include plumbing, carpentry, steel, drywall and rebar installation, and labor work. The least mentioned tasks include ceiling, electrical, scaffolding, and flooring work, mason, and ceiling work. The suggested tasks support reporting of industry databases (BLS, 2023) and research studies (Antwi-Afari et al., 2023; Gonsalves et al., 2023) that identified back-related injury as a concern in the construction industry. Some of the tasks suggested by the practitioners (e.g., carpentry work, rebar installation, concrete work, and masonry) were also identified by (Kim et al., 2019) as being suitable for exoskeletons. Similarly, Gonsalves et al. (2023) identified framing and plumbing as being more suitable for back-support exoskeletons.

Fig. 4: Word cloud of construction tasks that would benefit from active back-support exoskeletons.

4.2 Example of Prediction of Level of Exertion from Exoskeleton-Use

This study presents an example of predicting the levels of exertion due to exoskeleton-use. This section presents the performance of the 1-D convolutional neural network in classifying the levels of exertion during exoskeleton-use for a framing task.

4.2.1 Model performance evaluation

The accuracy of the 1D-CNN in classifying the levels of exertion due to exoskeleton-use for the framing task is 82%. The confusion matrix for the model is illustrated in Figure 5. The matrix shows that the model performed better in detecting the ME and HE classes than the LE class. For example, the model detected classes ME and HE with 100% accuracy and LE class with 67%. Furthermore, 37% of the LE class is mostly confused with the HE class.

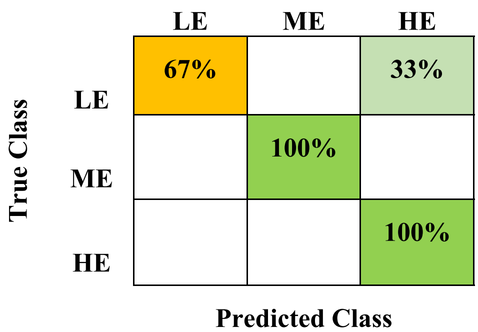

Fig. 5: Confusion matrix showing classification accuracies of levels of exertion due to exoskeleton-use.

From the precision (see Table 4), it can be observed that out of the times ME and HE classes were predicted, the model was correct 100% of the time. However, out of the times HE class was predicted, the model was correct 67% of the time. For the recall, out of all the times the HE class was predicted, only 75% of the class was correctly predicted.

F1-score explains a model's ability to both capture classes (recall) and accurately capture the classes (precision). The F1-score of the ME class is 100%, meaning that the model has a balanced ability to accurately capture all the ME classes from the data. However, in the case of the F1-scores of the LE and HE classes which are 80% and 75% respectively, the model will have a mixed reaction. For the LE class, while the model may be correct 67% of the time, all the LE class predicted will be correct. The findings of this study have shown the effectiveness of 1D-CNN in classifying EEG signals (Alzahab et al., 2021). The lowest F1-score obtained in this study is still high and can be compared to other construction-related studies (Xiong et al., 2022).

Table 4: Performance metrics for ID-CNN for the classes.

Classes	Precision	Recall	F1-score
LE	67%	100%	80%
ME	100%	100%	100%
HE	100%	60%	75%

4.2.2 Level of Exertion and Digital twin

The digital twin of the exoskeleton-users and the rating meter (shown in Figure 6) shows the level of exertion resulting from the results of the model. The digital twin shows an exoskeleton-user experiencing medium exertion. The meter comprises a pointer and three different colors, red, yellow, and green indicating high, medium, and low exertion respectively. The pointer reflects the level of exertion which is currently shown as medium exertion. Related studies have shown the possibilities of creating similar interfaces for data acquisition as a human-in-the-loop digital twin (Locklin et al., 2021). This exoskeleton risk assessment dashboard can also be extended to show the muscle activity, cognitive load, and fall rating of the exoskeleton user. This vital data collected via sensors can be useful for supervisors and managers to monitor workers while using the exoskeletons.

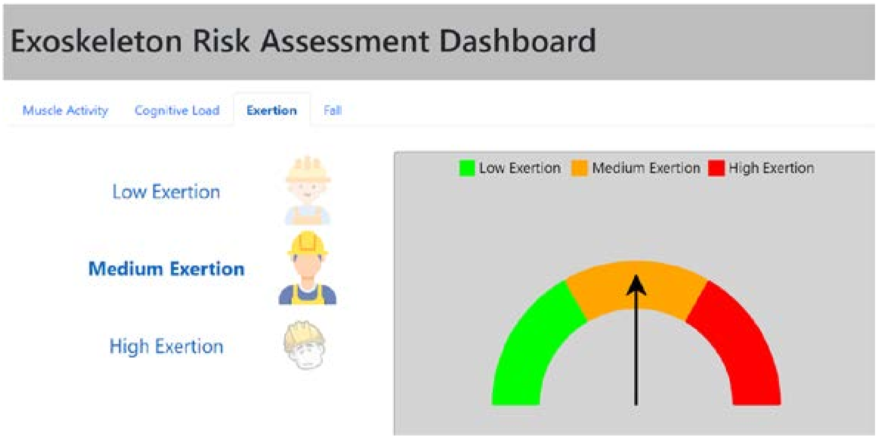

Fig. 6: Dashboard showing digital twin representation of the level of exertion.

5. CONCLUSIONS, LIMITATIONS AND FUTURE WORK

This study aims to investigate a digital twin framework for assessing the risks associated with exoskeleton-use for construction work. A review of the literature was conducted to identify risks associated with exoskeleton-use, and objective and subjective methods for assessing the risks. A system architecture was developed to illustrate the enabling technologies and their roles in supporting the proposed framework. Results of interviews with construction workers identified carpentry framing task as one of the construction tasks that can benefit from active back-support exoskeletons. Electrodermal signals were collected during the experimental simulation of the framing task with an active back-support exoskeleton. 1D-CNN trained to classify electrodermal data demonstrates the potential of the DT framework to predict the exertion levels of exoskeleton users during framing tasks. This study contributes to the scarce literature regarding the use of digital twins for assessing the suitability of exoskeletons for construction work. The study demonstrates the role of physiological sensing and machine learning techniques in facilitating the implementation of the digital twin framework. Furthermore, this study sets precedence for research involving the use of digital twins for performance monitoring of exoskeletons during construction work. Such efforts could promote the sustainability of exoskeleton solutions in the construction workplace. This study had some limitations which are currently being addressed in an ongoing study. Firstly, EDA data was generated from students engaged in a laboratory-based simulation of framing tasks. The use of experienced construction workers could produce data that can help develop prediction models that are generalizable for the construction population. Secondly, only the exertion levels using the EDA data was modeled to demonstrate the digital twin framework. Further work will involve other sensing technologies and the prediction of other physical and psychological risks. Future studies will also involve a user assessment of the digital twin framework with intended users.

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URBAN CENTERS MANAGEMENT: A DIGITAL TWIN APPROACH

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ABSTRACT: *The management of the built environment is a topic that requires reference to the management of complex systems. In fact, the variety of domains involved means that the management of urban centers is not only complicated, and therefore it is not enough to model a set of rules that are representative of phenomena related to the real environment. Not only that, but what is evident is that emergency management lacks the ability to access real-time information that could be decisive. Having tools that provide real-time data, that reprocess it, and that are able to provide an enriched and slightly predictive view of what is happening offers the possibility of having a real impact in the management of the built environment. In this sense, digital twins are a valuable approach to achieving the desired results. Digital twins through the integration of technologies such as lnternet of Things (IoT), simulators, Artificial Intelligence (AI), and Augmented Reality (AR) technologies make it possible to develop systems capable of exploiting the concept of collective intelligence, in a digital version, through a large number of heterogeneous agents working according to stigmergic mechanisms. This research work aims to propose its own architecture of digital twins for the management of resilient urban centers, with particular reference to the management of post-earthquake reconstruction scenarios.*

KEYWORDS: *Digital twin, urban environment management, urban centers, smart cities, emergency management, BIM.*

1. INTRODUCTION

The 2030 Agenda for Sustainable Development (Agenda, 2030) has set 17 Goals among which Goal 11 is defined as follows "Make cities and human settlements inclusive, safe, resilient and sustainable." In addition, there is a recent trend that identifies an increasing population shift to urban centers. According to the United Nations, over 55 percent of the world population inhabited cities in 2008, with the percentage expected to rise to 68 percent by 2050 (UN 2019). All of this implies the need to rethink cities focusing not only on the sustainability of these centers of aggregation but also with the intention of making them resilient to change and responsive to unexpected events.

It should be noted that urban centers, cities are complex organisms (De Toni et al., 2013). This implies that it is impossible to manage the processes affecting them through rules, but a holistic and integrated approach is needed. One approach that has been pursued for years to the problem of managing urban centers is the development of smart cities. The term smart city is said to have first appeared in the middle of the 1990s, when the cities promoted themselves after introducing new information and communication technology (ICT) infrastructure or e-governance services, or when attracting technology companies to provide new economic growth to the region (Hollands, 2008). Anyway, a smart city should go beyond the mere use of ICT systems. It is expected that a smart city should improve the quality of life of its citizens, while simultaneously simplifying the management of the city. In some cases of developing smart cities the term "smart" was referred to an automated mechanism introduced to perform the desired activity within a given domain (Ahad et al., 2020). Other smart city paradigms relate technology more directly with innovation and human capital development, based on the concept that technology can give a city's constituents the power to innovate, create, participate in society and solve problems collectively for the common good (Angelidou, 2015). In any case the current research on smart city does not fully address the complex nature, conflicts and interdependencies of the smart city objectives (Shamsuzzoha et al., 2021).

Meanwhile in recent years we assist the rise of Building Information Modelling (BIM) approach in a wider way than the one that wants it to represent but a small part (a narrow building-level view) within the wider environmental context. BIM's massive introduction into the processes of the built environment has led to a higher level of digitization of all kinds of information, as this approach allows the achievement of high performance only when embedded in digital systems and platforms. This evolution of BIM should be carefully framed within a paradigm that factors in people, processes and new emerging technologies in an increasingly interconnected world (Boje et al., 2020).

In this scenario it is expected that residents of future smart cities will be exposed to unprecedented amounts of

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Alessandra Corneli, Marianna Rotilio, *Urban Centres Management: A Digital Twin Approach*, pp. 1245-1254, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.122

real-time information on a daily basis (Du et al., 2020). This data also coming directly from people and equipment and assets can contribute to the development of a stigmergic system. Stigmergy is a communication method used in decentralized systems by which individuals in the system communicate with each other by modifying their surroundings and leaving traces (Debreu Netto et al., 2015). Indeed, the scenario of the 21st century is increasingly characterized by interactions between the physical and virtual worlds, thanks to the progressive creation of a global connective space with a high intensity of information flows, the potential of Information Communication Technology (ICT), as well as the Internet of Things (IoT), of Big Data, Virtual and Augmented Reality, and the spread of progressively more powerful computational devices, whose high processing capabilities, albeit without discretion, are being defined, namely the so-called Artificial Intelligence and Machine Learning, and related predictive algorithms (Cinquepalmi and Pennacchia, 2020). All this leads to a currently emerging paradigm and that is the Digital Twin (DT) paradigm. Other industrial sectors than construction have been developing digital twin-based concepts over the past decade, but this approach has made its first appearances in the AECO sector only over the past few years. Digital twins are a digital replica of their real counterparts. A DT is always a representation and for this reason unlike its physical counterparts, it is not an all-or-nothing proposition. DTs can be tailored so as to choose to collect information only about features that have value for the stakeholders involved or for the aim it is developed for. There is a crucial aspect in DT that differs them from simulation models and even common smart cities paradigm (Fig. 1) and it is prediction. Numerous examples have shown how digital twins can continuously monitor operations and identify abnormal behaviors, allowing human operators to react promptly and reduce downtime (Arup, 2019). In any case in the longer-term, it is evident that no single DT will be sufficient for modern complex cities: in a smart city scenario, independent DTs of various assets will need to communicate and cooperate, providing feedback to a central decision making "hub" or city-level decision makers (Pregnolato et al., 2022).

This paper presents a framework for implementing digital twins in urban centers. Building on what DA (Silva et al., 2018) showed as a technology for the smart city, our proposal is to include a reasoning layer through real-time data, which is one of the aspects that differentiates DT from the rest: short- to medium-term forecasting to provide decision support to the decision makers involved. The scenario that is particularly referred to is that of emergency management. Since city management requires dealing with complexity the digital twin is the ideal method to take into account different data and analysis in an integrated way. Starting with an analysis of the scientific bibliography concerning the digital twin and smart cities illustrated in the next section, the article aims to focus on real-time management and the insights that DTs can offer to support the management of the unexpected. Case study on which to implement the proposed framework will be presented.

2. LITERATURE REVIEW

Performing a search on the Web of Science, using the keywords "digital AND twin* AND "urban" AND "cit*" in

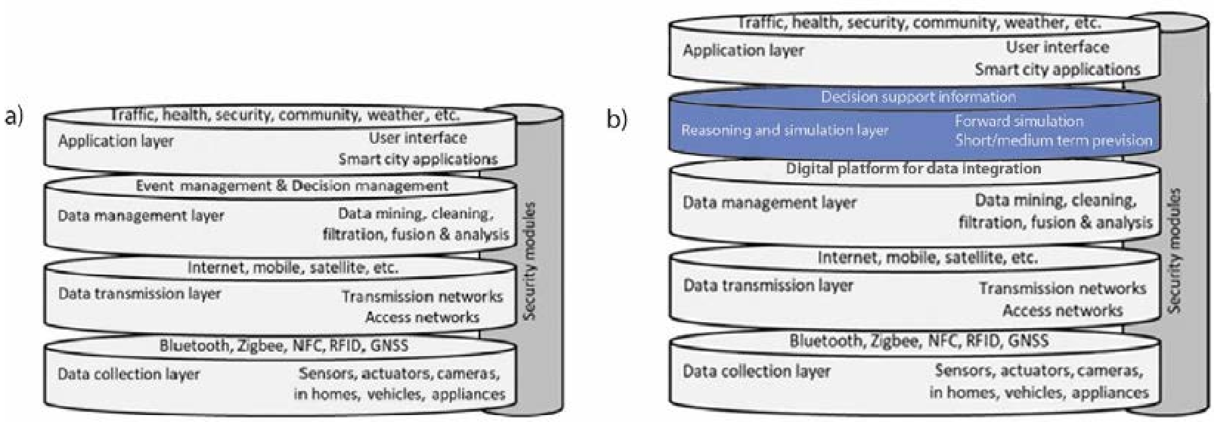

Fig. 1: a) Smart city architecture proposed by Silva et al., 2018; b) DT architecture whose fundamental layer that differentiates this from Smart Cities is the Reasoning and simulation layer that allow for short/medium term previsions supporting prompt decision-making particularly significant during emergencies.

a time range from 2006 to the present, yielded a total of 379 articles, most of them in the area of Computer Science (21.1%) and Engineering (17.8%)(Fig. 2). Particularly in relation to the latter area, there were only 153 papers in total (Fig.2). Furthermore, the metric analysis showed that most of the publications are concentrated in the last

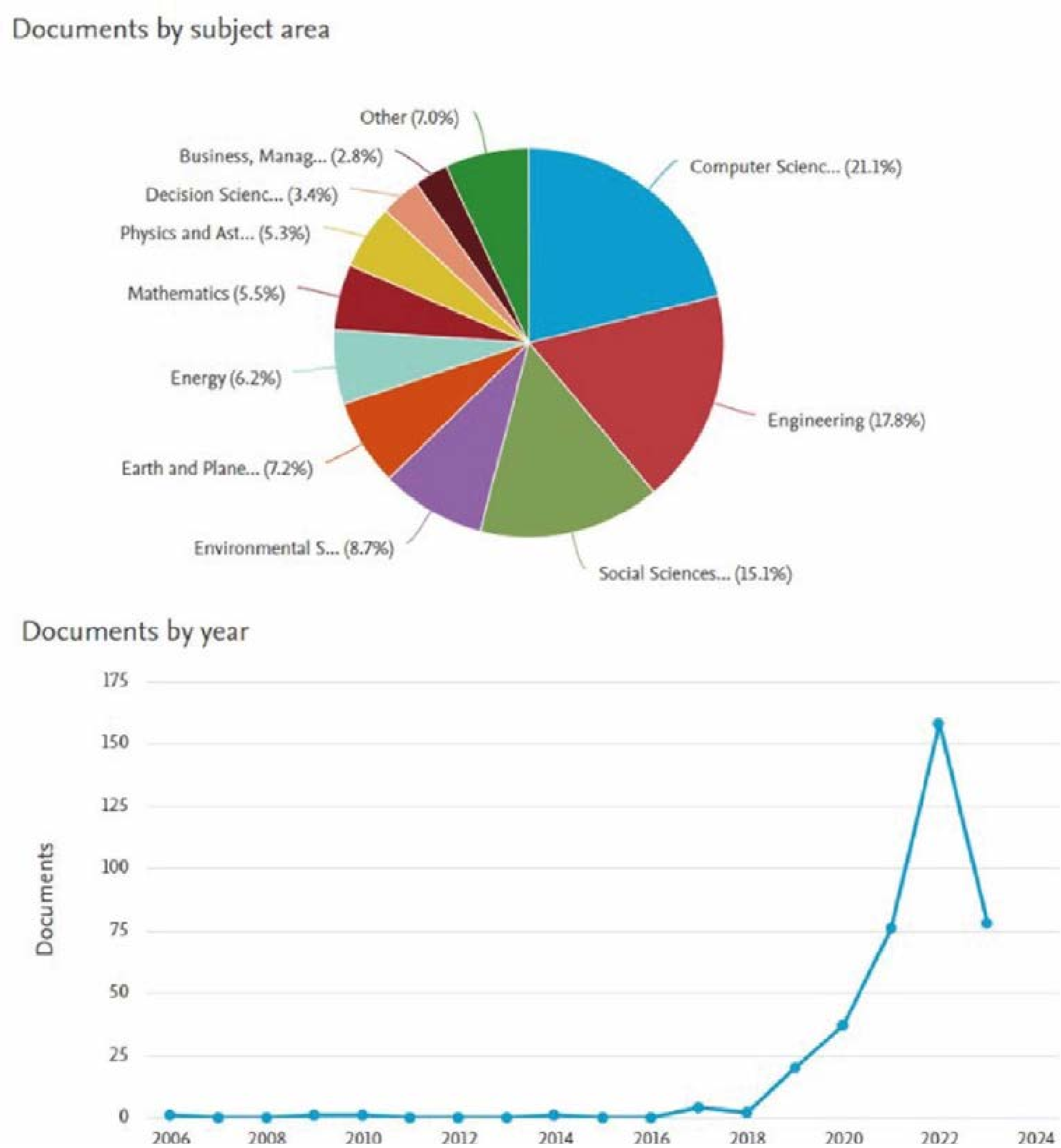

Fig. 2: The graph above shows the number of papers containing the terms “digital”, “twin” and “urban” in the period from 2006 to 2023 divided by subject area. The graph below instead shows the trend (referred to the same period of time) of papers with the same key words comprised in the area of Engineering. The spike in the adoption of certain terms from the years 2021-2022 is evident.

five years, i.e. from 2018 to the present (Fig. 2). This data highlights how the topic is of recent interest in the international scientific community. From the 153 articles identified, a screening was first carried out by reading the titles of the articles and discarding those of no interest. Subsequently, the abstracts were read and the search areas were identified. These ranged from the topic of infrastructure and urban mobility to that of the construction and built environment. For each area, an article of particular interest to the study was identified, argued below and summarized in Table 1.

Gang Yu et al. (2021) focus on urban infrastructure, proposing a digital twin framework for the operation and maintenance of tunnels. Haishan Xia et al. (2022) analyze the BIM GIS relationship within the digital twin framework used to support smart city development. The study is also conducted in the area of infrastructure, in relation to rail transport. Salem and Dragomir (2022), on the other hand, develop a literature analysis of the construction project management using digital twin approach. Lv et al. (2022), Corrado et al. (2022) and Nica et al. (2023) carry out their research in the field of urban planning, also from a sustainable perspective (Corrado et al., 2022; Nica et al. 2023). In particular, Lv et al. reflect on the importance of using DTs urban platform to improve the future planning vision. Yu et al. (2023) analyze the support that new digital technologies can offer in the creation of smart cities, as does Wenhua Huang et al. (2022) in relation to the Internet. Other areas of interest are those concerning the use of the Digital Twin for the management of the built environment (Rotilio et al., 2023) and urban mobility (Yeon et al., 2023).

The research performed showed that the topic of DT in support of smart cities is an area of study of recent interest within the international scientific community and that it is addressed in specific areas, lacking a global and multidisciplinary approach. This research gap highlights how further research is needed, which this article aims to help bridge. Indeed, the main objective of the research presented here is to provide a framework that, based on a DT approach, supports the management of the complex contexts typical of post-disaster reconstruction in which many issues and disciplines converge. A demonstrator will be presented for framework validation.

Table 1: Summary of the main references analyzed

Reference, year	Aim of the research	Results	Search area	Case study
Gang et al., 2021	To propose a digital twin-based decision analysis framework for the O&M of tunnels	Results show that the framework can provide efficient and automatic decision analysis support for the O&M of tunnels	Urban infrastructure maintenance, operation and evaluation	Fault cause analysis of fans in Wenyi Road Tunnel in Hangzhou, China
Haishan et al., 2022	To study the combination BIM and GIS for the urban digital twin to support sustainable smart city design	A professional disconnect and fragmented composition pose challenges in the field of GIS and BIM integration. Future research should focus on smart city planning, updating, management; ontology-based GIS and BIM data integration platform; and operation; and the collaborative management of urban rail transportation engineering	Rail trasportation	-
Salem and Dragomir, 2022	To review the literature on construction project management through the lens of digital twins	Authors propose a framework for analyzing and supervising the development of digital twins that uses three main stages: the BIM; the existing monitoring and actuation digital twins; the artificial intelligence	Construction area	-
LV et al., 2022	To promote the expansion and adoption of Digital Twins (DTs) in Smart Cities (SCs)	The construction of DTs urban platform can improve the city's perception and decision-making ability and bring a broader vision for future planning and progression.	Urban planning	-
Corrado et al., 2022	To propose a comprehensive approach that takes the multiple facets of sustainable urban planning into consideration	A metric-driven framework for sustainability planning that understands a city as a sociotechnical complex system was proposed	Sustainable urban planning	Buildings in the Technical University of Crete campus
Nica et al., 2023	To inspect the recently published literature on digital twin simulation tools, spatial cognition algorithms, and multi-sensor fusion technology	Internet-of-Things-based smart city environments integrate 3D virtual simulation technology, intelligent sensing devices, and digital twin modeling	Sustainable urban governance networks	-
Yu et al., 2023	To study whether and how current practices based on digital twin technology can help the development of smart cities in China	The research provide suggestions for the development of digital twin technology-based ecosystems in emerging economies	Smart cities	China
Wenhua et al., 2022	To propose a basic concept of digital twin, and gives the construction method and possible applications of the energy internet digital twin	The key problems solved by digital twin technology are detailed and CloudIEPS, an energy internet planning platform based on digital twin, is introduced	Urban infrastructure	-
Rotilio et	To realize a first extended	Digital Twin is exploited as an adaptive	Built environment	DT

al., 2023	framework enabling the implementation of digital twins in the built environment	system for the built environment, as a support to optimize post-disaster reconstruction processes with a focus on reactive security management		demonstrators in the laboratory
Yeon et al., 2023	To introduce DTUMOS, a digital twin framework for urban mobility operating systems	DTUMOS is a versatile, open-source framework that can be flexibly and adaptably integrated into various urban mobility systems. His novel architecture combines an AI-based estimated time of arrival model and vehicle routing algorithm	Urban mobility	Large metropolitan cities including Seoul, New York City, and Chicago

3. RESEARCH METHODOLOGY

The proposed application framework for the development of DTs to support the management of urban centers begins with the identification of needs. It should be kept in mind that a DT however comprehensive is always a representation of certain components of reality. For this reason starting from the identification of needs or we could say critical issues for which decision support is desired can begin to design the digitization of the real world. This analysis can only start from the dialogue with the stakeholders concerned, the administrators of the territory (Public Administrations) and the decision makers who will then be the end users of the product.

The critical issues and needs thus identified lead to a second analysis concerning which aspects, parameters or agents need to be monitored in order to collect data useful for managing the identified issue. The connection in fact between the real world and the digital world is given by the Data Integration Layer (that will be better explained in the next section) which collects data through the use of the most suitable technologies. The choice of the latter also comes from a thorough analysis not only of what data needs to be collected but also of the context, the instrumentation possibilities of the environment, the data transmission technologies themselves, etc. Once the data have been collected and integrated with each other, we move on to the use phase.

As previously mentioned what makes a digital twin different from simulation systems is the ability to make short- and medium-term predictions by exploiting collective intelligence. To do this, it becomes necessary to identify the best tools for this intelligence to emerge and be recognizable and interpretable. Artificial intelligence tools, Bayesian networks, and game engine-type agent simulators are some of the possible means of interpreting data by highlighting patterns or recognizing behaviors, applying multifactor interaction knowledge on problems, or performing high repetitions of random simulations to probe all possible scenarios. Depending on the data collection method, the subsequent possible processing also varies and thus the choice of the two components of the DT is strongly influenced.

Finally, the last aspect that profoundly affects the system is how the information resulting from the processing can be transmitted to the relevant stakeholders. The first choice to be made is whether it will be information used in the back office or directly on site. In both cases, the solution involving the implementation of a cloud platform is the best since it allows more immediate access to the data even from smartphones. In the case of information displayed directly on site in addition to the previously mentioned smartphones, solutions involving augmented, diminished or mixed reality can also be used. Although tools for displaying information as holograms are not yet widespread on a large scale, the power of superimposed visualization is for many applications of extreme importance. However, it should be kept in mind that recently registration techniques are being developed such that overlay visualization can be achieved even with the much more common smartphones.

In the following paragraph the application of what was introduced in the methodology will be translated into the architecture of the proposed system.

4. A FRAMEWORK FOR THE IMPLEMENTATION OF DIGITAL TWIN IN URBAN ENVIRONMENT

We are sometimes faced with some confusion in differentiating simulation systems from actual digital twins. There are two main characteristics that put together determine and differentiate a DT from the rest: real time and short- and medium-term prediction. The forecasting capability that is the one that most characterizes a DT is achieved by an intelligence component that can predict unexpected situations and propose optimized solutions based on data from the physical layer in real time. The proposed integration methodology for an optimal DT implementation involves the development of a framework architecture that consists of four layers added to the physical one: the data acquisition layer, the data integration layer, the digital twin modeling layer and finally the user interface layer renamed the presentation and service layer (Fig. 3).

The physical layer refers, in this case, to the urban environment that is the object of the digital twin. Buildings, roads and facilities of cities are all considered since this will enable a valuable support to decision. The different level of scale of assets covered and the multi-domain visualization of information integrated with each other will provide a look at all crucial aspects at once.

Data acquisition layer (Data collection layer in Fig.1-b) is a functional representation of the interface between the physical layer and the framework and is aimed to fetch data to digital models. In this layer are managed gathering technologies and transportation data protocol parsing. Data can be divided into two distinct categories: static and dynamic data. Static data are related to the configuration of context, thus not changing continuously. It includes preliminary survey data and characterization of physical asset (e.g. BIM and GIS models, Point Cloud models, etc.). The purpose of collecting these data on an urban scale is to report a representation of the built environment as built and in its current state of preservation. Given the heterogeneity of the type of constructions objects of the representation (buildings, roads, bridges, infrastructure) data will also have heterogeneous formats and sizes, as well as different scales of representation of the data. Dynamic data on the other hand are related to observations about relevant aspects for the behavior simulation of the physical system. Dynamic data are typically transported in XML or JSON format. Cameras, wireless sensors, citizens' smartphones can all contribute to the acquisition of

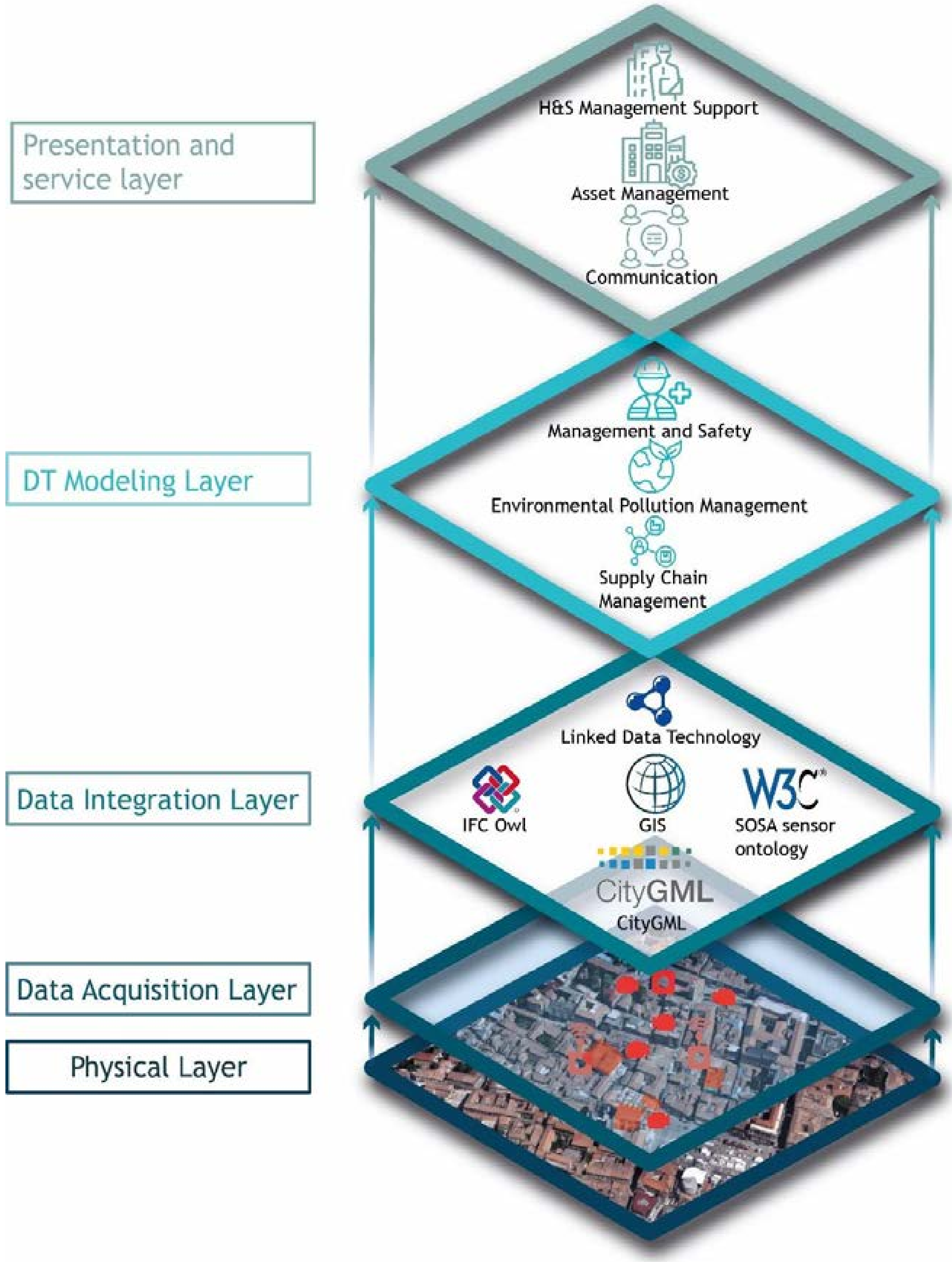

Fig. 3: DT for uban centres proposed architecture.

dynamic data, and by wisely choosing their placement these help create a stigmergic environment in which it is the assets, equipment, and people themselves (whether workers or citizens) that supply the DT with data.

Representation could be solved with the adoption of the Semantic Sensor Network Ontology (SOSA). SOSA ontology is recommended by the World Wide Web Consortium (W3C) for describing sensors and their observations, the involved procedures, the studied features of interest, the samples used to do so, and the observed properties, as well as actuators. Procedure for data acquisition optimization are fundamentals so as to avoid huge amounts of useless gathered data to analyze and improve the efficiency of the system.

Data Integration Layer will be in charge of integration of data at different scales (such as BIM and GIS representations), of different formats, and multidisciplinary. Beside this first task of data integration layer it has to be taken into consideration that most of popular data models (e.g. IFC, CityGML) do not claim to be based upon a formal Top Level Ontology since they have been developed pragmatically over years, and have been validated by practice. After the definition of the industrial exchange format IFC (Industry Foundation Classes), an important step in the direction of extending the scope of building data models is the recent introduction of IfcOWL ontology standard which is the Web Ontology Language format of IFC. This advance goes towards the embracement of Web of Data technologies to model the context of interest (buildings and assets). On the same line, research methodological approach is inspired by the expected benefits obtainable with Web of Data technologies such as the ability to granularly link data from different models. Web of Data consists of two technologies that are built upon the basic Web then relying on Universal Resource Identifiers (URIs) and Hypertext Transfer Protocol (HTTP): Semantic Web: RDF (Resource Description Framework) for graph-based data representation, and OWL (Web Ontology Language) for specification for shared conceptual models; Linked Data: Principles for specifying the interrelations and access across different datasets.

Both technologies contribute to the specification of the shared meaning of entities, one of the crucial problems in interoperability. This approach allows to support the integration of BIM models represented in IfcOWL with other building data referred to various ontologies directly in RDF; so many XML-based formats will also be supported such as CityGML-based format (for city scale representation) or sensor and observations data ontologies.

Then there remains the issue of data that are unstructured or do not have their own ontologies. This aspect for what concerns DT at the urban scale is extremely relevant since the vastness and heterogeneity of the elements taken into account makes the possibility of interfacing with multidisciplinary and multiscale data very realistic. A powerful framework therefore having to take this into account should contain the possibility of including new ontologies for both data and semantic links between structured and unstructured data. The framework proposed envisages the possibility of sharing data stored in RDF repository on the Web so that users can access them in a granular manner. Besides graph-based data model, schema/ontology languages, serialization formats, and query/reasoning languages, should provide a RESTful API technology for clients to interact with data.

Data Integration Layer can be mapped to Data Transmission Layer in Fig. 1-b because they methods shown also provide the means by which to communicate some of the data itself.

DT modeling layer (Data management layer plus Reasoning and simulation layer Fig. 1-b) is a virtual layer ideally containing the Digital Twin model or models. These differ according to the purposes for which they are implemented (e.g. in Fig.3 one DT for supply chain management, one for environmental pollution management and the last for H&S management). This layer contains the digital copy of the asset and the simulation tools for behavior forecasting. In the framework here proposed DTs are thought to be distributed over the cloud and connected to the framework via the internet. Different DTs are implemented by using domain specific algorithms and tools and are fed by Data Integration Layer through the REST Interface. Any DT internal structure is highly dependent on its specific domain and scope. Nevertheless, it must have a normalized external interface to link itself into the framework. Such interface is minimal and includes following data flows (usually in XML/JSON format): first configuration parameters and variables, time synchronizing clock, input and output streaming and exposed variables shared with the framework.

Finally, the presentation and service layer (Application layer Fig. 1-b) is a virtual layer on top of the framework that enables interaction with people/stakeholders. It corresponds to the RESTful API interface for retrieving information from the model integration bus. This layer is designed as a layer for distributing information to external management systems and specific user interfaces. This layer allows interaction with the population, thus also defining the DT as a tool for improving communication with and active participation of the citizenry. On the other hand, this layer is also the one that allows customers or decision makers to visualize data and possible suggested corrective actions. Again, the services toward which one can strive are diverse: three possible outputs of DTs are shown in Fig.3, namely support for site safety management, support for decision makers involved in real estate asset management, and communication with the public. It is at this level that the services that the digital twin will take care of are defined in detail, and so in a reverse engineering effort we start from here to understand at the root what data will need to be collected to meet certain set purposes.

5. CASE STUDY: L'AQUILA

The application for the proposed framework is the municipality of L'Aquila, in Abruzzo region, Italy. L'Aquila is a municipality that well represents the previously mentioned concept of complexity. First of all, it is a city that is located in an earthquake zone and periodically subjected to earthquakes that then result in subsequent states of emergency. L'Aquila is a historic city, and this entails two fundamental aspects: on the one hand, the city's housing stock is likely to be more fragile, less resilient to change, and with historical and artistic value to be preserved at the same time. On the other hand, its being an ancient city means that some infrastructure especially in the city center has drawbacks: narrow streets, uneven paving. All these aspects put together make the DT paradigm a very efficient and comprehensive method for dealing with problems.

The case we wanted to focus on is the implementation of a digital twin for safety support at construction sites and more specifically with regard to prop removal operations. In the most common post-earthquake scenarios, there is a frequent need to realize temporary shoring mainly for safety purposes, related to the use of the buildings themselves and of the adjacent public spaces (Fig. 4). Despite being conceived as temporary, the shoring is frequently intended to last more than a decade, often without undergoing revision or maintenance. Frequently they also create hindrance to the viability and free road travel because they occupy portions of public land. It is for this reason that their removal for the execution of recovery operations is a particularly delicate phase. This first demonstrator aims to test the ability of the proposed framework to integrate urban impact models of a construction site taking into account criticalities related to the removal of temporary shoring. The dismantling of this system is of great interest because it determines significant impacts in reconstruction sites, both in terms of operators' safety and organization and management.

The proposed DT will work by projecting short- and medium-term forecasts based on data streams generated by monitoring networks. These networks enable early warning strategies based on real-time predictive analysis of collected data, while also performing high-speed and qualitative simulations to assess specific risks and behaviors. The sensor network defines a fourth-level monitoring system, that is, a system that can estimate the location and extent of damage and use this data to determine the state of the overall structure, and thus its level of safety. The reference models are a simplified version of the FEM model simulator, linked to the HBIM model of the building aggregate, or structurally connected set of buildings. The DT thus implemented will work on three types of data sources: [a] sensor data from a network of sensors installed in the building aggregate and on temporary shoring, with the intent of monitoring relative displacements of structural elements, subsidence, and deformations, and [b] data communicated in real time through the sensors, arising from neighboring construction sites related to ongoing activities and positioning, vehicles and thus additional vibrations generated, and [c] contextual data communicated in real time related to urban processes that may interfere with or be jeopardized by the simple execution of temporary shoring removals or collapses.

This will enable the DT to provide valuable support during the reconstruction phase when the dismantling of temporary shoring may lead to the definition of deformation close to sudden collapse conditions. At the same time, the DT will integrate and interpret the data from the sensor network based on the three previously identified sources and generate an early warning if the limit values are exceeded. In this way, the decision maker will be informed and will be able to activate the necessary measures: stop work, if necessary, and evacuate the surrounding area. In addition to this, the DT integrated in a communication platform with the population will provide information about the works in progress so as to provide support to the citizen. Indeed, the latter could change his or her route by car if the site's workings block the passage or his or her walking route also in relation to the possible dust emissions reported by the DT. Finally, the continuous application of DT during the management and operation of the building stock could facilitate the transition from scheduled maintenance to an "on-demand" approach, in which the building itself communicates the necessary maintenance actions. Specifically, during the execution of consolidation work, the building aggregate will be equipped with a network of sensors aimed at conducting structural monitoring. The collected data are exploited to verify the performance of the buildings over time, allowing a continuous assessment of their safety and the opportunity to plan appropriate rehabilitation activities to reduce their vulnerability. The results in terms of process innovation introduced by the proposed research will support actors involved in the reconstruction and management of smaller historic centers, particularly site safety coordinators to coordinate and plan removal work.

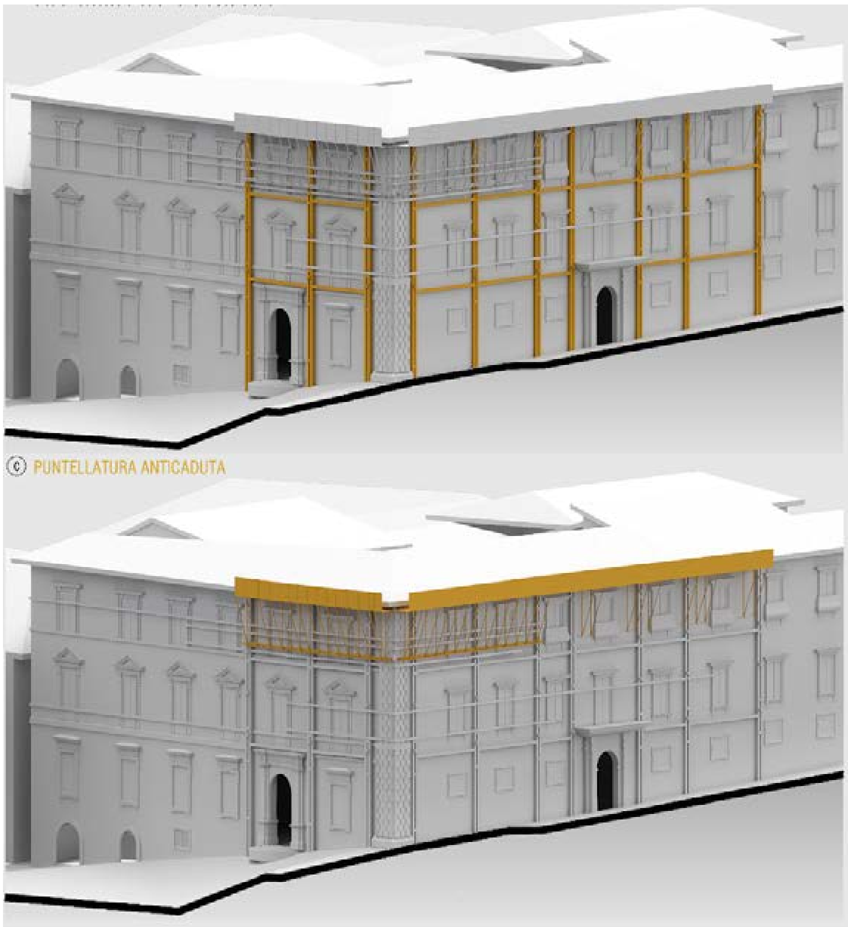

Fig. 4: Examples of shoring in HBIM for a historic building.

6. CONCLUSION

This paper presents a framework for implementing a digital twin in an urban environment that by its definition is characterized by complexity. The scenario chosen is that of post-earthquake emergency management and subsequent reconstruction phases. The configuration of an integrated system such as DTs that collect real-time data directly from the physical context allows for stigmergic systems. These imply that it is directly the environment, or rather the agents within it, that leave information on the ground for other agents. Inolte the DT through real-time simulation systems and data analysis is able to provide short- and medium-term forecasts that ensure decision support, both for stakeholders involved in land management, for those responsible for the construction and repair phases, and for the community.

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DIGITAL TWINS FOR SMART DECISION MAKING IN ASSET MANAGEMENT

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ABSTRACT: *This study discusses the classification of Digital Twins (DTs) and their use in the Architecture, Engineering, Construction, and Operations (AECO) industry, the differences between building information modeling (BIM) and DT are emphasized and platforms for implementing DTs are compared. DTs are quickly gaining traction in the AECO industry because they create the ability to interact virtually with all physical smart devices in the built environment. The need for replicas goes all the way back to the 1960s, when NASA created physical replicas of spaceships and connected them to simulators to develop workshop solutions on the ground. DTs are simply building blocks of the metaverse that act as a real-time digital copy of a physical object. Based on data from the physical asset or system, the physical twin (PT), a DT unlocks value in supporting smart decision-making by combining artificial intelligence (AI) with the internet of things (IoT).*

KEYWORDS: *Digital Twins; Internet of Things; Artificial Intelligence; Asset Management.*

1. INTRODUCTION

Digital Twins (DTs) are quickly gaining traction in the AECO industry are quickly becoming synonymous with smart cities because they create the ability to interact virtually with all physical smart devices. DTs allow us to integrate in a physical environment data and information on what is happening in that environment thus converting that physical environment into a virtual one, that can be used in real time, or in aggregate, to facilitate the analyses of physical spaces.

In the AECO industry, the focus on DTs has increased due to the proliferation of digitalization and integration processes. For example, there has been a marked growth in the development of Building Information Modeling (BIM), but while BIM has instigated the digitalization and integration of design and construction information, its utility for smart decision-making in the postconstruction stage is limited as the data and information captured in BIM outputs are static. Consequently, the need for technology that enables dynamic optimization of BIM data and operational data has grown. DTs have shown early promise in the AECO industry to elevate BIM from static to actionable and dynamic virtual models.

2. BACKGROUND

The path from building information modeling (BIM) to DTs involves the integration of multiple data sources (see Fig. 1).

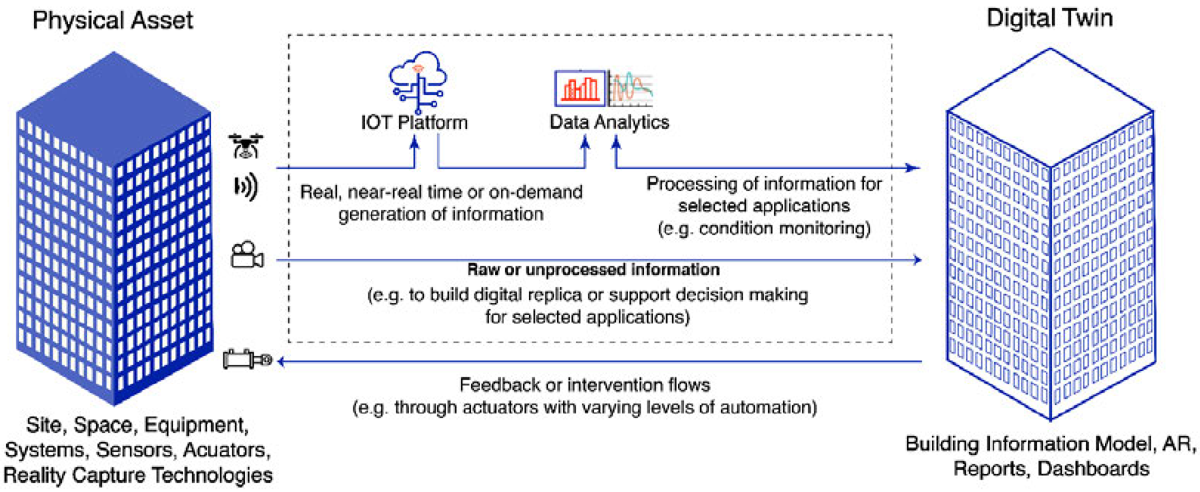

Fig. 1: Essential components to create a DT of a building (Adapted from Khajavi et al. 2019)

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Chady Elias, Raja Issa, *Digital Twins for Smart Decision Making in Asset Management*, pp. 1255-1260, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.123

2.1 Building Information Modeling (BIM)

BIM as a digital technology continues to stimulate new workflows in the AECO industry. The capabilities of BIM to generate three-dimensional visualizations, and data rich models have resulted in its extension to facility lifecycle activities including facility management, operations and maintenance (O&M), commissioning and close-out, energy management, and space management, all key aspects of FM (Becerik-Gerber et al. 2012). Major progress has been made in the efficient transfer of design and construction data to FM systems, e.g., Computerized Maintenance Management Systems (CMMS), by using open standards, e.g., Construction Operation Building information exchange (COBie). Identification and specification of the required data during the facility design stage and requiring appropriate BIM deliverables is essential to developing models which are beneficial to facility managers. The data allows facility managers to analyze operational data while allowing owners a complete view of their assets (Asare et al. 2021).

Selecting the proper BIM level of development (LOD) is crucial in successfully developing a DT. The LODs for sharing building information models with project participants, as prescribed in the American Institute of Architects (AIA) E202 contract (AIA 2022), range from LOD 100 to LOD 500 (see Table 1). BIM, specifically the LOD 500 model, is the foundation of the Existence DT. The next step in the integration of BIM, FM and O&M lies in the development of DTs.

Table 1. AIA E202 LODs (AIA 2022)

§	Levels of Development (LOD)
4.2	**100:** The Model Element may be graphically represented in the Model with a symbol or other generic representation. but does not satisfy the requirements for LOD 200. Information related to the Model Element (e.g., cost per square foot. tonnage of HVAC, etc.) can be delivered from other Model Elements.
4.3	**200:** The Model Element is generically and graphically represented within the Model with approximate quantity, size, shape, location, and orientation.
4.4	**300:** The Model Element, as designed, is graphically represented within the Model such that its quantity, size, shape, location, and orientation can be measured.
4.4.1	**350:** The Model Element, as designed, is graphically represented within the Model such that its quantity, size, shape, location, orientation, and interfaces with adjacent or dependent Model Elements can be measured.
4.5	**400:** The Model Element is graphically represented within the Model with detail sufficient for fabrication, assembly, and installation.
4.6	**500:** The Model Element is a graphic representation of an existing or as-constructed condition developed through a combination of observation, field verification, or interpolation. The level of accuracy shall be noted or attached to the Model Element.

2.2 Internet of Things (IoT)

The internet of things (IoT) presents us with opportunities for transforming work and everyday life. The IoT is at the intersection of the physical and digital worlds, with all kinds of devices harnessing the power of interconnectivity to provide seamless experiences for businesses and consumers alike. To reach its full potential, IoT has to shift from continuing to provide incremental value amid siloed clusters to unlock its vast potential value as a fully interconnected IoT ecosystem. This will require an integrated IoT network within and across all industries. The main obstacle to be confronted is the cybersecurity risk which detrimentally impacts the trust needed to integrate IoT applications and networks. For smart cities, as with other applications, the expected solution lies in the merging of IoT and cybersecurity to form a new, integrated system (Greer et al. 2019).

2.3 Digital Twins (DTs)

A DT is comprised of three principal parts: a physical system in real space, the physical twin (PT); a virtual system in cyberspace, the DT; and the connection between real and cyber space for transferring data and information using cyber-physical systems and the internet of things (CPS/IoT). A DT creates an accurate digital model of the physical system in cyberspace that can accurately replicate and simulate the behavior of the PT. According to Tao et al. (2018), a DT can also provide a digital footprint of products by integrating geometry, structure, behavior, rules and functional properties. Salvador Palau et al. (2019) noted that DTs can also be considered as intelligent agents with prediction, communication, and data preprocessing capabilities.

Kritzinger et al. (2018) distinguished the various digital forms and categorized them as digital model, digital shadow and DT based on the automated dataflow between them (see Fig. 2). The Digital Model is a digital representation of an existing or planned physical object that does not use automated data exchange between the physical object and the digital object. Changes in the state of the physical object have no direct impact on the digital object and vice versa. The Digital Shadow is derived from the Digital Model and represents one-way data flow between the state of an existing physical object and a digital object. A change in state of the physical object leads to a change of state in the digital object, but not vice versa. The DT is characterized by automated bi-directional data flow between the physical and digital objects, which possess intelligence and decision-making capabilities that enable the automated feedback loop to the physical entity. A change in state of the physical object directly results in a change in state of the digital object and vice versa.

The combination of the PT and its corresponding DT is the fundamental building block of fully connected and flexible systems that are able to learn and adapt to new demands. Some of the DT roles include remote monitoring, predictive analytics, simulating future behavior, and optimization. To fulfil these roles, DTs rely on certain capabilities that exist across all of them. These required DT capabilities are summarized as follows (Redelinghuys et al. 2020):

- Acquire PT state - The DT must be able to acquire data from a variety of sensor types (e.g., temperature, pressure and vibration sensors and counters or PLC registers) from the PT. The PT sensor data collected is refined and enriched (e.g., through combination and adding context) into information sets that describe the state of the PT.

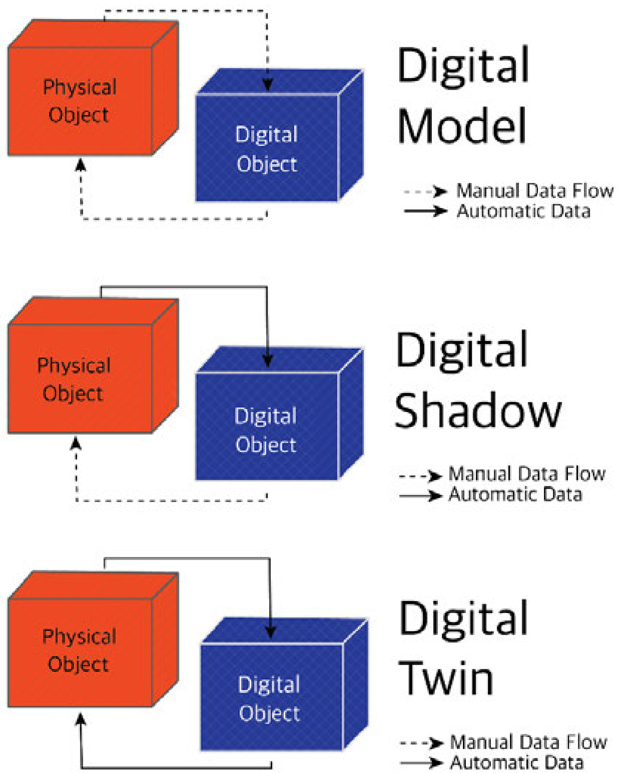

Fig. 2: Evolution from Digital Forms to Digital Twins (Adapted from Kritzinger et al. 2018).

- Maintain Information Repository - The state information obtained from the PT sensors is stored for easy access through the internet. This repository typically relies on Cloud-based storage, since large volumes of data may be stored for long periods of time.

- Simulate operation - The simulation of the PT's operation, i.e., predicting its future behavior from a given starting state and selected set of conditions, is required for some of the envisioned roles of the DT including the evaluation of new processes and different operation schedules.

- Emulate operation - Using emulation to imitate and visually represent or reproduce the action or function of the PT in real-time using feedback from embedded sensors.

Changes in the physical process will impact the digital world through the feedback of real-time embedded sensors and actuators. Using this data feedback, digital models can be used to interpret the behavior of machines or systems, and predict future state from real-time and historical data, as well as experience and knowledge. The core elements of a DT are the models and data. CPS, and the technologies required for developing CPS, are considered as a necessary foundation for implementing DTs.

Major challenges to adopting DTs include global connectivity, data integration and interoperability, data standardization, security and integrity, real-time performance and reliability, as well as barriers to its implementation and legacy system transformation (Attaran and Celik 2023). These challenges play a fundamental role in the development of DTs, as the connections between the PT and its corresponding DT typically rely on internet enabled connectivity.

3. CLASSIFICATIONS AND LEVELS OF MATURITY

There is not one single definition for what a DT is or the capabilities it provides. There are numerous types of DTs and levels of functionality based on the needs or the organization or project and the maturity of the data available. The development of a DT is a continuum, with the model evolving with the addition of new data and capabilities, the following classifications were developed by KPMG (2022) to indicate the level of functionality of the DT based on the types and level of data and capabilities that the system provides (see Figure 3):

- Existence twin: Furnishes principal project information, e.g., details on asset location and properties, enabling a single source of truth for asset data across the project. Traditional CAD and BIM systems are examples of an existence twin. This DT definition differs from that of the Kritzinger et al. (2018) classification of the evolution from digital forms to DTs.

- Status twin: Provides information on the status and condition of assets as detected by embedded IoT sensors. This can provide important insights into construction quality and progress, as well as asset health status over its lifecycle, and enables prediction of future performance based on the data collected.

- Operational twin: Allows for a real-time view of the project and the operational asset. This can provide critical insights into real-time performance and risks, both during construction and operations, and it enables more informed decision-making.

- Simulation twin: Enables teams to assess the impact of different design, construction, and operational decisions, allowing optimization of improvements in cost, performance, and risk. A simulation twin enables better and more thorough planning and can help minimize the risk of costly design and construction errors and faulty operational control changes.

- Cognitive twin: Uses AI and real-time data collection to analyze data, make decisions and optimize operational performance. This enables refinements made in real-time based on live data to adapt to existing conditions.

These classifications imply that an organization does not need to develop a highly advanced and complex model to see value from investing in DT technologies. For example, existence and status DTs can provide important project management insights on the physical configuration, properties, budget and cost, and as-built condition of a project and its component assets.

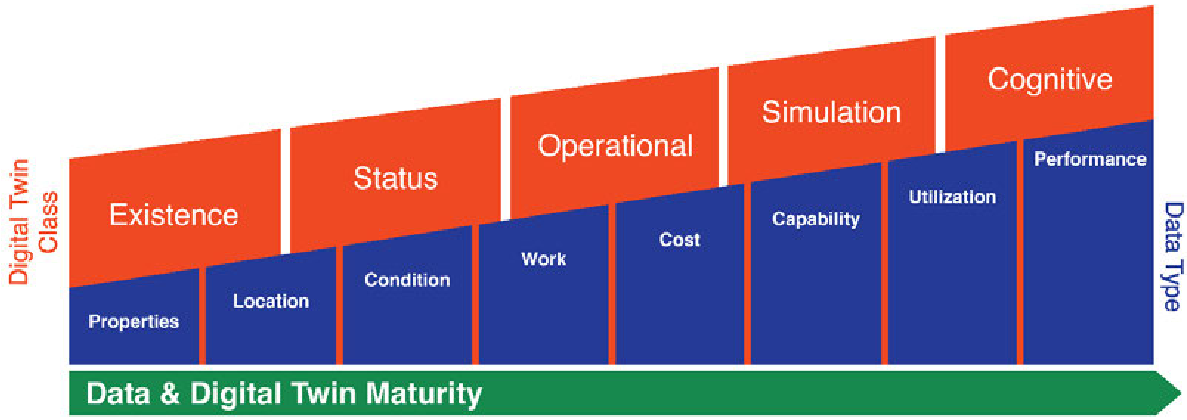

Figure 4. Data and DT Maturity (Adapted from KPMG 2022)

4. DIFFERENCES BETWEEN BIM AND DT

The building information model focuses on replicating the physical asset throughout the asset's lifecycle, while the DT replicates and enables a connection with the physical asset during operations. In BIM, there is total split between the digital and the physical asset, while, for DTs this split is distorted due to asset instrumentation and data synchronization between the physical and the digital asset. BIM is used in the three main phases of the built asset's lifecycle, design, build, and operations (Brilakis et al. 2019), while the DT is focused primarily on operations. These models have varying degrees of detail for their specific use-cases, i.e., built asset design, design-construction coordination, optimal asset delivery, and facility management. For DTs, there are no standard specifications for model detail or fidelity available. BIM has limited support for asset monitoring and control and for asset performance simulations during operations, while the DT does not consider discipline coordination for built asset delivery (Delgado and Oyedele 2021).

5. PLATFORMS FOR IMPLEMENTING DTs

There are three categories of data platforms for implementing DTs (Adamenko et al. 2020):

1. IoT Platforms: They provide data connectivity between the real and virtual world. Typically equipped with resources that establish connection between networked devices and the applications that process and/or visualize the data. Examples include Azure Digital Twins and IoT, Amazon Web Services IoT TwinMaker, Siemens MindSphere and Eclipse. DT design with such tools is more data-based. They provide a user interface (UI) for data modeling.

2. Gaming Engines: These platforms facilitate the development of executable video game-like applications. Their high-end visualization capabilities can be combined with IoT Platforms to achieve user-friendly DT applications. Examples include Unreal Engine, and Unity 3D. They require extensive programming to model DT data.

3. Commercial modeling and Simulation Platforms: These tools typically support design and implementation of system-based DTs. Examples include ANSYS, Autodesk Tandem, NVIDIA Omniverse, Microsoft Azure and Unreal Engine. They each provide a user interface (UI) for data modeling, e.g., Digital Twin Definition Language (DTDL) based on JSON-LD for Azure models, and the Universal Scene Description (USD) language for the Omniverse platform.

6. CONCLUSION

DTs provide a new outlook for smart decision-making in the AECO industry. From an operations and maintenance perspective, DTs can provide a dynamic view of facility status, enable operational control, support scenario planning and testing, and afford overall operational intelligence. To achieve high-performing DTs for smart decision-making, it is important to develop high-quality BIM outputs and supplement them with high-fidelity data. This requires a clear understanding of the different types of DTs, the tools for developing them, as well as knowing how and where to apply DTs. A macro-level roadmap to transforming BIM to DTs has been presented. As adoption of DTs increases, it is important to address the issues of standardization of DT design and implementation. This includes testing implementation tools and methods towards identifying the creation of DTs that can truly make decision-making in the AECO industry smarter.

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Within the overarching theme of "Managing the Digital Transformation of Construction Industry" the 23rd International Conference on Construction Applications of Virtual Reality (CONVR 2023) presented 123 high-quality contributions on the topics of: *Virtual and Augmented Reality (VR/AR), Building Information Modeling (BIM), Simulation and Automation, Computer Vision, Data Science, Artificial Intelligence, Linked Data, Semantic Web, Blockchain, Digital Twins, Health & Safety and Construction site management, Green buildings, Occupant-centric design and operation, Internet of Everything.* The editors trust that this publication can stimulate and inspire academics, scholars and industry experts in the field, driving innovation, growth and global collaboration among researchers and stakeholders.

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ISSN 2704-601X (print)
ISSN 2704-5846 (online)
ISBN 979-12-215-0289-3 (PDF)
ISBN 979-12-215-0257-2 (XML)
DOI 10.36253/979-12-215-0289-3
www.fupress.com