TOWARDS CONSTRUCTION SAFETY MANAGEMENT MATURITY MODEL IN THE INDUSTRY 4.0 ERA: A STATE-OF-THE-ART REVIEW

Nazi Soltanmohammadlou, Sara Rashidian, Carol K.H. Hon, Robin Drogemuller & Sara Omrani
Building 4.0 CRC, Caulfield East, Victoria, Australia and School of Architecture and Built Environment, Queensland University of Technology (QUT), Brisbane, QLD 4001, Australia

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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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.

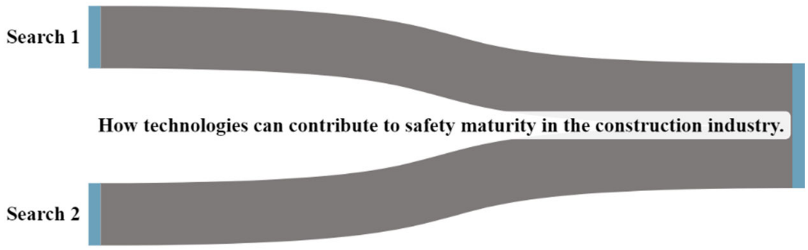
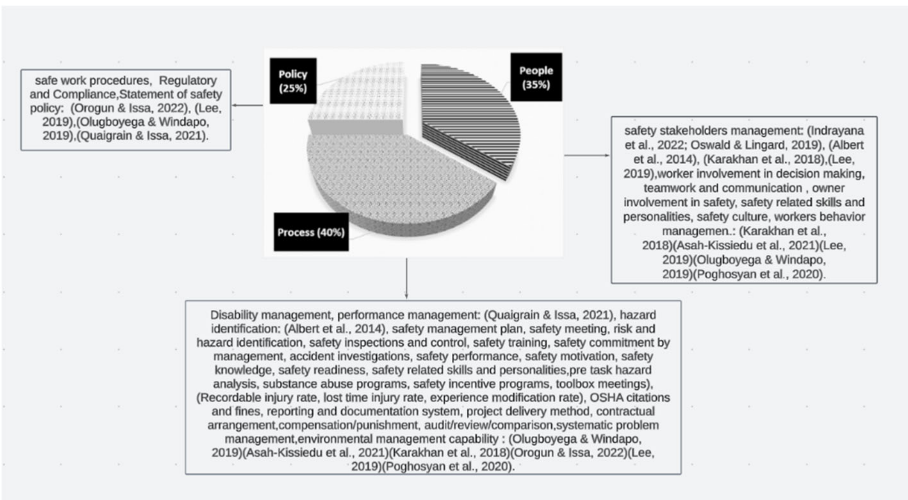


Fig 1. The goal of combining the findings from two-phase searches

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.

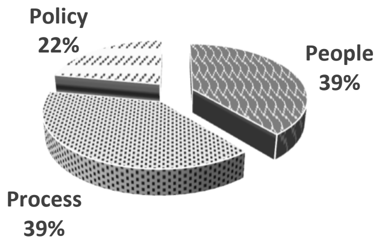


Fig 3. Publication distribution by industry 4.0 technologies applications

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.

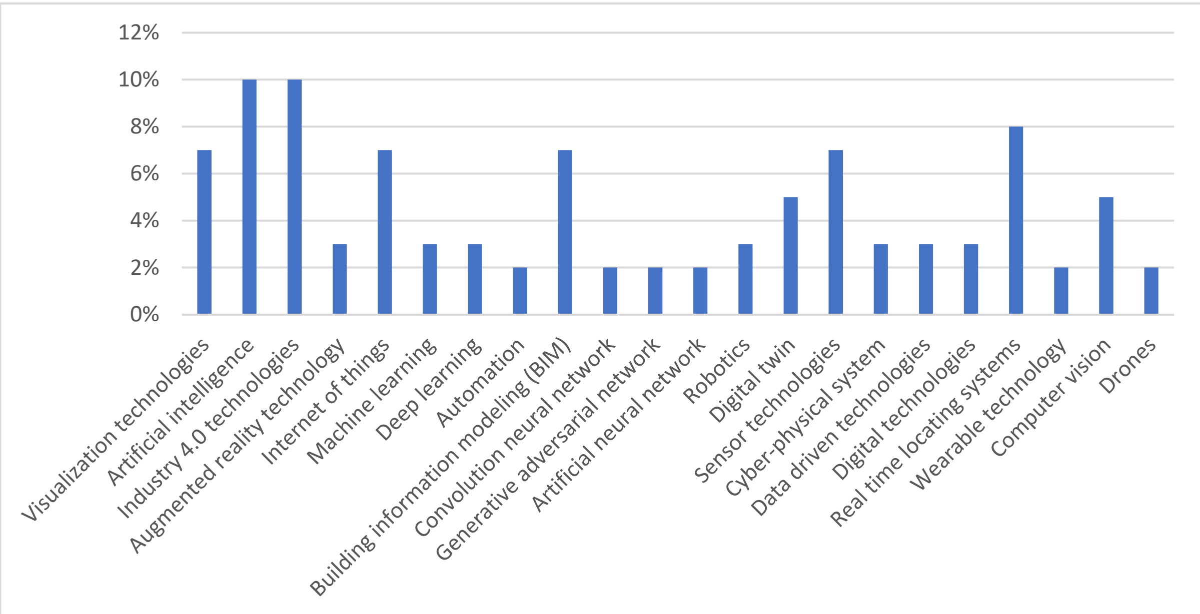


Fig 1. Publication distribution by industry 4.0 technologies type

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.

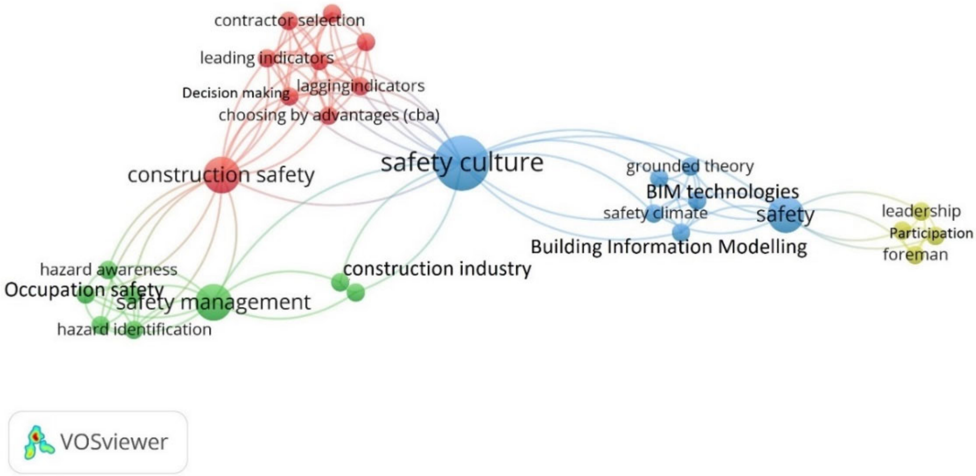


Fig 2. Co-occurrence of keywords of safety maturity models extracted from phase one of the search

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.

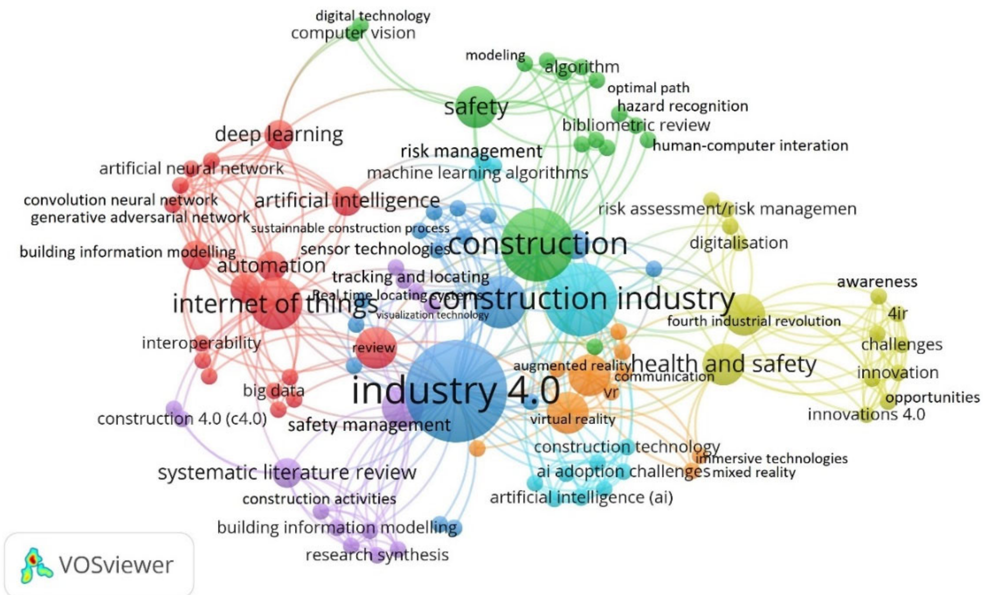


Fig 3. Co-occurrence of keywords of application of industry 4.0 technologies in construction safety extracted from phase two search

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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