Lecture Notes in Civil Engineering

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4th International Conference "Coordinating Engineering for Sustainability and Resilience" & Midterm Conference of CircularB "Implementation of Circular Economy in the Built Environment"

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Preface

As Organizers of the CESARE 2024 and CircularB Midterm Conference, we are honoured to present the Proceedings of the 4th International Conference on "Coordinating Engineering for Sustainability and Resilience" and the Midterm Conference of the COST Action CircularB on "Implementation of Circular Economy in the Built Environment", held in Timişoara, Romania, from the May 29th–31st 2024.

This volume, published in Open Access by Springer, a prestigious publishing company, embodies our commitment to disseminating critical research and innovations in Engineering for Circular Economy, Sustainability and Resilience.

Society and governments require a more efficient and sustainable built environment. An emergent trend is the Circular Economy, which aims at decoupling economic growth from resource consumption. Construction has been identified as a field of action by the European Commission's Circular Economy Action Plan.

The 4th International Conference on the *Coordinating Engineering for Sustainability and Resilience* & Midterm Conference of CircularB *Implementation of Circular Economy in the Built Environment* is co-organized by the Steel Structures and Structural Mechanics Department of the Politehnica University Timişoara, in co-operation with the Romanian Academy, the School of Engineering of the University of Birmingham, the Faculty of Engineering of the Jordan University of Science and Technology, the COST Action CA21103 "Implementation of Circular Economy in the Built Environment" and the Technical Sciences Academy of Romania.

The CESARE 2024 and Midterm CircularB Conference is devoted to the presentation of the most recent results and to the discussion of key issues concerning the contribution of Coordinating Engineering to Sustainability, Circular Economy and Resilience in modern and future built environment, constructions, and infrastructure.

One of the main goals is to promote an exchange of ideas that inspires innovative research paths and fosters new collaborative endeavours. We expect to have an impact on the future research and development activity in all topics included in the programme.

169 authors from 31 countries on five continents are contributing with 63 scientific papers and two Keynote Lectures, covering ten topics, i.e.

1. *Sustainable Infrastructures:* This chapter lays the foundation for integrating sustainability into infrastructural development, highlighting innovative practices that minimize environmental impact while enhancing social and economic benefits;
2. *Structural Engineering:* Focusing on the core principles of engineering for resilience and sustainability, this chapter discusses cutting-edge designs and technologies that ensure the longevity and durability of structures in the face of environmental challenges;
3. *Energy Systems and Structures:* Examines the integration of sustainable energy systems within built environments, showcasing solutions that reduce energy consumption and carbon footprint;

4. *Innovation in Materials, Products, and Systems:* Highlights revolutionary materials and systems that are setting new standards for sustainability and efficiency in construction and design;
5. *Circular Value Chains and Stakeholders Engagement:* Discusses the importance of creating circular value chains and engaging stakeholders in collaborative efforts to foster a Circular Economy within the built environment;
6. *Circularity KPIs and Criteria for Material, Flow and Design Assessment:* Details the key performance indicators and criteria essential for assessing and optimizing circularity in materials, design, and workflow processes;
7. *Circular Business Models and Economic Viability of Circularity Solutions:* Analyses various circular business models, emphasizing their economic viability and potential to drive sustainable industry practices;
8. *Environmental Impact of Circularity Strategies and Solutions:* Explores the environmental implications of circularity strategies, focusing on their potential to mitigate environmental degradation and promote sustainability;
9. *Standards and Regulations:* Provides an overview of the current standards and regulations that shape sustainable and circular practices in the built environment, highlighting challenges and opportunities for policy development;
10. *Digitalisation and BIM for Circular Design and Evaluation in Construction:* Concludes with an examination of how digitalisation and Building Information Modelling (BIM) are revolutionizing circular design and construction, offering new pathways for efficiency and sustainability.

The contributions within these pages are a demonstration to the constant pursuit of knowledge and innovation by our global community. They cover a vast array of topics, from Sustainable Structural Engineering to the implementation of Circular Economy principles in the built environment, all aimed at addressing some of the most pressing challenges of our times.

It is our hope that this Open Access publication will serve not only as a repository of high-quality research but also as a catalyst for further study, discussion, and innovation. By making these contributions freely available, we aim to ensure they are consulted, cited, and impactful, driving positive change in our society and beyond.

We extend our deepest gratitude to all contributors, reviewers, and our publishing partners at Springer for their invaluable support in bringing this work to the broader community. May this Book of Proceedings inspire and facilitate ongoing efforts to engineer a sustainable and resilient future for all.

The Organizers of the CESARE 2024 and CircularB Midterm Conference.

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Keynote Papers

Life-Cycle Risk, Resilience, and Sustainability of Individual and Spatially Distributed Structures

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Abstract. Field investigations after recent large earthquakes have confirmed that several structures were severely damaged and collapsed not only by the earthquake, but also by the subsequent tsunami, landslide, or fault displacement. Effect of material degradation due to chloride attack on structural performance should be considered when structures are located in a harsh environment. In addition, climate change has produced typhoons and hurricanes with extreme intensity in recent years. Sea-level rise could cause severe storm surges and tsunamis, and global warming is accelerating the deterioration of structures. When structures are exposed to these different types of hazards, it can be difficult to ensure their safety and additional performance indicators such as risk and resilience are needed. Several lessons were learned about the importance of investigating individual structures from the perspective of ensuring network functionality. A probabilistic life-cycle framework for quantifying the loss of functionality of road networks including bridges is needed. A risk-based decision-making approach at the network level is required to identify the dominant hazard and the vulnerable structures that require strengthening and retrofitting. After a catastrophic event, the functionality of transportation networks can be significantly degraded, resulting in catastrophic economic impacts. To quantify the promptness of recovery, it has become common to use the concept of resilience. In addition, the economic, environmental, and social impacts of disaster waste management systems need to be examined in terms of sustainability. Consequences related to resilience and sustainability need to be investigated and implemented in the risk assessment of road networks under multiple hazards. Life-cycle design and assessment methodologies can incorporate risk, resilience, sustainability and multiple hazards, learning from the lessons of past disasters. This keynote paper provides an overview of measures to ensure the functionality of individual and spatially distributed structures under multiple hazards from the perspectives of reliability, risk, resilience and sustainability.

Keywords: Life-cycle · Multiple Hazards · Reliability · Risk · Resilience · Road Network · Sustainability

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1 Introduction

As observed in recent disasters in Japan (e.g., 2011 Great East Japan earthquake, 2016 Kumamoto earthquake, and 2024 Nota-Hanto earthquake), since transportation networks, including bridges, play a crucial role in evacuating affected people and transporting relief goods and materials, the functionality of the network after a disaster needs to be investigated. A significant amount of research has shifted the focus from investigating the performance of individual infrastructure components to that of entire distributed civil infrastructure systems and networks [1]. Rapid recovery of critical infrastructure system functionality after an extreme event is always a goal of paramount importance [2, 3].

To quantify the speed of recovery, it has become common to use the concept of resilience. Resilience emphasizes the impact of infrastructure damage, failure, and societal recovery under low-probability and high-consequence hazards. Sustainability, on the other hand, focuses on current and future resource management and addresses the impacts of planning and development on the economy, society, and the environment. A sustainable infrastructure system must incorporate resilience and adaptability to ensure its long-term sustainability. In fact, some of the most promising solutions for resilience are also sustainable in nature [4].

The design and assessment of structures has focused on addressing the most dominant hazard at the site of interest. However, the possibility that structures may experience multiple hazards of different types during their lifetime needs to be considered. Bridge design methodology needs to shift to a more comprehensive approach of addressing multiple hazards to ensure adequate performance under different mechanical and environmental scenarios [5]. Quantifying the reliability and risk of each bridge under multiple hazards can help prioritize retrofit activities for bridges in a network.

Significant progress has been made in the field of earthquake engineering. However, further research is needed to develop concepts and methods for designing and evaluating resilient and sustainable bridges and bridge networks in a life-cycle context. This paper provides an overview of life-cycle design and assessment methodologies for bridges under multiple hazards, with emphasis on independent and interacting hazards, based on lessons learned from recent major earthquakes in Japan. Several performance indicators that need to be implemented in practical design and assessment are presented. Finally, case studies are used to illustrate the concepts and methods presented.

2 Lessons from Recent Large Earthquakes in Japan

Figure 1 shows several destructive earthquakes that have occurred in Japan since the 1995 Kobe earthquake. The lessons learned from these earthquakes indicate that in addition to seismic safety, other performance indicators of individual bridges and bridge networks need to be considered. The 2024 Noto-Hanto earthquake, as well as the 2011 Great East Japan earthquake, caused structural damage due to strong excitation, tsunami, landslides, and liquefaction. The 2024 Noto-Hanto earthquake demonstrated that an earthquake is a source of multiple hazards which can cause a variety of adverse effects on structures and infrastructure systems. In this section, several types of damage are reported, mainly from the results of the field investigation conducted after the 2024 Noto-Hanto earthquake.

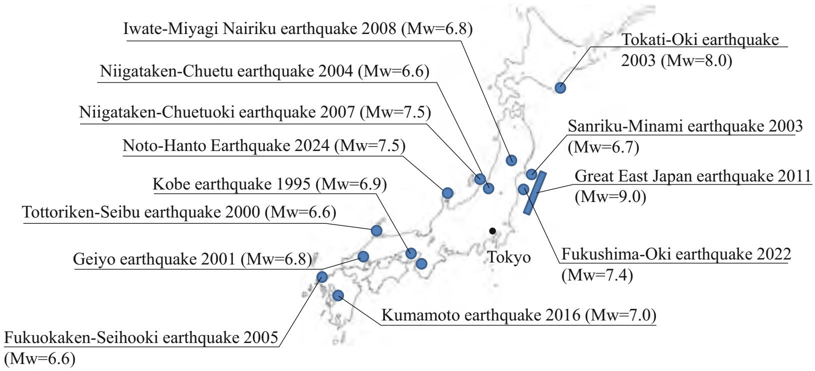


Fig. 1. Large earthquakes in Japan after the 1995 Kobe earthquake.

Compared to the ground motion- and tsunami-induced damages to bridges during the 2011 Great East Japan earthquake, the number of bridges affected by the 2024 Noto-Hanto earthquake was limited. Figure 2 shows the damage to Ukai Bridge with three simple skewed girders constructed in 1960. Total length of Ukai Bridge is 54 m. Three simple girders for pedestrians were parallel to the decks for vehicles. As shown in Fig. 2, two of the pedestrian girders collapsed, which may be caused by the deck rotation seismic response of skewed decks for vehicles. However, one of them was washed away by the tsunami as shown in Fig. 3. It was displaced more than approximately 50 m from its original position. Tsunami waves created water pressures due to the impulse of breaking waves, and dynamic pressures that varied with wave velocity and height [6]. It is sufficient force to blow away even concrete members of considerable weight. The damage to the Ukai Bridge shown in Figs. 2 and 3 indicates the need for countermeasures that take into account the effects of both strong ground motions and tsunamis. However, as shown in Fig. 3, it is extremely difficult with current bridge technology to prevent damage to bridges from a tsunami strong enough to blow away the superstructure. Therefore, it is important to avoid placing bridges in high tsunami hazard areas or to create routes that pass through areas without high tsunami hazard to ensure the functionality of the network in terms of redundancy.

Around the Ukai Bridge, there were many old wooden houses that were built before seismic design methods were established in Japan. They did not appear to have been seismically retrofitted. As shown in Fig. 4, many of them were severely damaged by earthquake excitation, tsunami, and/or liquefaction. The Noto Peninsula experienced an earthquake with the moment magnitude of 6.7 in 2007, which damaged many wooden houses. Since some of them were not repaired and retrofitted, the 2024 Noto-Hanto earthquake may have caused further damage. In addition, water and sewage pipes were seriously damaged in many areas of the Noto Peninsula. Figure 4 shows a manhole that has popped out due to liquefaction. Although it is difficult to seismically strengthen underground water and sewer pipes, the 2024 Noto-Hanto earthquake demonstrates the importance of retrofitting them to ensure the continued use of tap water and toilets, which are essential to the daily lives of people in the affected areas.

Fig. 2. Sidewalk collapse of Ukai Bridge subjected to ground motion and/or tsunami caused by 2024 Noto-Hanto earthquake. Note that the picture was taken by the second author.

Fig. 3. Washout of Ukai Bridge sidewalk due to tsunami caused by the 2024 Noto-Hanto earthquake. Note that the picture was taken by the second author.

The effect of corrosion on the deterioration of bridge capacity under seismic hazard must be considered. The Noto Peninsula faces the Sea of Japan and is known as one of the harshest environments in Japan due to airborne chloride. During the winter season, the wind mostly blows from the west (i.e., Japan Sea), bringing airborne chloride. Many concrete bridges deteriorate due to steel corrosion. Recently, some of the bridges that were repaired to remove chloride in the concrete and replace the cover concrete with corrosion cracks are deteriorating again, as shown in Fig. 5. As discussed in Sect. 3, it is important to understand that the seismic demand depends on the seismic hazard, while the seismic capacity depends on the other hazard, such as the hazard associated

Fig. 4. Collapse of classical wooden Japanese houses due to ground motion, tsunami and/or liquefaction caused by the 2024 Noto-Hanto earthquake. Note that the picture was taken by the second author.

Fig. 5. Bridge redeterioration due to chloride attack after repair near Noto Penisula (Note that the picture was taken in 2017 by the second author)

with airborne chlorides [7]. The seismic performance of existing bridges in a harsh environment cannot be expected to be the same as that at the time of construction [8].

In Japan, following the tsunami caused by the 2011 Great East Japan earthquake, large areas of farmland were flooded with salty water and contaminated with marine sediments, resulting in long-term soil contamination of highly fertile agricultural land with metals and metalloid compounds [9]. As a result of the earthquake and subsequent tsunami, approximately 23 million tons of disaster debris were generated, with more than 12 million m^3 of tsunami deposits remaining in the flooded area. The amount of disaster waste generated by the 2024 Noto-Hanto earthquake is limited compared to that generated by the 2011 Great East Japan earthquake, but it must prevent the affected

Fig. 6. Tsunami damage in Suzu City and disaster waste generated by the 2024 Noto-Hanto earthquake. Note that the picture was taken by the second author.

region from recovering from the disaster. Figure 6 shows an example of the disaster waste generated by the 2024 Noto-Hanto earthquake.

The structural and geotechnical utilization of the concrete and soil fraction in the disaster debris and tsunami deposits has posed a great challenge to engineers because (a) the removal of the debris and tsunami deposits is an urgent task that must be completed within a few years [10], and (b) although a large amount of waste concrete and soil can be recycled and used in reconstruction, their properties have temporal and spatial variations [11]. If poorly managed, these wastes can have significant environmental and public health impacts that can affect the overall recovery process and undermine sustainability [12].

3 Toward Life-Cycle Based Design and Assessment of Bridges and Bridge Networks Under Multiple Hazards

3.1 Progress of Structural Performance Methodology and Associated Performance Indicators

Figure 7 shows the evolution of structural design methodology from deterministic allowable stress design to life-cycle based design and assessment of transportation networks that include bridges. Traditionally, structural safety in design is quantified by comparing the structural capacity to the load. In the allowable stress design method, the designer simply ensures that the structural components have a fraction of the elastic limit state for the service loads. Static and linear elastic analyses are performed to estimate the demand at the component level. With the development of computer technology and computer simulation capability, and with the lessons learned from disasters, structural design methodology has progressed to include consequences of structural failure, various performance indicators, and life-cycle concepts for bridges and bridge networks under multiple hazards. More details of these advances are reviewed in [13].

It is not feasible to design a bridge that will remain intact under all hazards that may affect its performance. Under excessive interacting hazards on bridges, such as seismic and tsunami hazards, and seismic and landslide hazards, it is quite difficult to identify the solution in terms of structural control to prevent the failure of bridges with damage due to strong ground motion under the cascading giant tsunami or huge landslide. The technology may not exist to increase the structural ductility and integrity of bridges against damage and collapse, even if additional requirements beyond those provided in

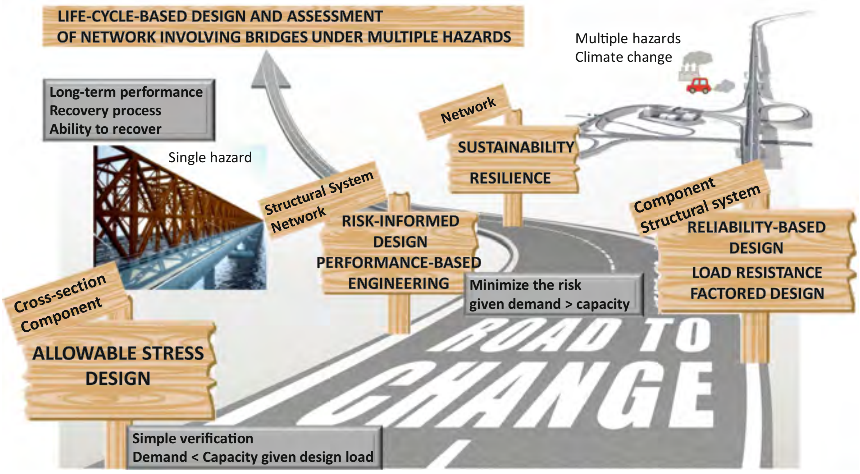


Fig. 7. Progress of structural design methodology: from the classical allowable stress design method toward the life-cycle based design and assessment of network involving bridges under multiple hazards.

current structural codes are required. Therefore, the concept of risk and resilience should be introduced. Before presenting studies that investigate risk, resilience and sustainability through quantitative approaches and application to case studies of bridge structures as described later, an idea of the contribution to risk reduction and resilience that comes from structural control is provided herein.

To maximize the post-event operability of bridges against extremely large earthquake excitations, the novel RC bridge pier with the sliding pendulum system has been proposed [14–17]. As a sliding pendulum, the upper component of the bridge pier moves on a sliding surface of the lower component of the bridge pier under strong excitation. In order to achieve cost-benefit, no flexible isolator layers were included in the bridge pier to extend the natural period; only conventional concrete and steel were used in addition to 3D printing technology. Computational and experimental investigations demonstrated that a damage-free bridge pier could be achieved under strong earthquakes.

Compared with the conventional girder bridges, a rigid frame bridge has the potential of being a robust and resilient structure against catastrophic actions such as fault displacement, huge landslide, and hydrodynamic forces associated with tsunami and flood. Since the rigid frame structures do not have bearings between the superstructure and substructure, they could prevent the washout of the superstructure due to the tsunami attack compared with the conventional girder bridge. Figures 8(a) and (b) show that the abutment of the Aso-Choyo Bridge could not support the PC box girder after it was transversely displaced by the landslide during the 2016 Kumamoto earthquake. However, since both the superstructure and substructure were rigidly connected and behaved as a continuous unit, the severe damage to the Aso-Choyo Bridge due to the landslide was not observed. Only after the reconstruction of the abutment, as shown in Fig. 8(c), the Aso-Choyo Bridge became functional and could contribute to the disaster recovery of the affected region.

Fig. 8. Example of robust structures against catastrophic hazards (a) and (b) taken after the 2016 Kumamoto earthquake; and (c) taken after the reconstruction of the abutment. Note that all pictures were taken by the second author.

Fig. 9. Washout of superstructure due to the 2020 Kyushu flood and reconstruction of temporary bridge using the survived bridge piers in Kuma River. Note that the picture was taken by the second author.

Considering the possibility that many bridge superstructures would be washed away during a future tsunami or flood event, solid technologies must be developed to enhance the disaster resilience of communities under seismic or flood hazards [13]. In Japan, since the structural details of bridge substructures (i.e., bridge piers and foundations) have been determined to ensure sufficient seismic performance, they could survive hydrodynamic attacks, as shown in Fig. 9. Surviving substructures were reused to construct a temporary bridge superstructure after, for example, the 2011 Great East Japan earthquake and the 2020 Kyushu flood, as shown in Fig. 9. A technology for the rapid construction of temporary bridge superstructures is needed to ensure rapid restoration and improve disaster resilience. Accelerated bridge construction (ABC) is an important research topic for this purpose. ABC using prefabricated elements saves on-site construction time and improves work zone safety [18].

3.2 Multiple Hazard Issues

A strong earthquake could cause multiple disasters, including damage to structures due to strong ground motions and/or liquefaction, and washout of structures due to subsequent tsunamis and landslides. In addition, seismic performance would be degraded due to material corrosion, fatigue, and scour caused by the flood, among others. Comparing the life-cycle reliability and risk of structures in a network under multiple hazards is useful for identifying significant hazard scenarios. A discussion of various design and analysis aspects for bridges under multiple hazards in a life-cycle context is provided herein.

Independent Hazards
Different types of hazards such as independent hazards, correlated hazards, concurrent hazards, and cascading hazards have been studied in the literature. The seismic reliability of corroded bridges or bridges damaged by flood scour is an example of the independent hazard cases. Figure 10 shows a general seismic fragility analysis procedure that considers the effect of steel corrosion on the deterioration of RC components. However, it's quite difficult to apply the procedure to evaluate the seismic capacities of corroded RC columns for developing the numerical fragility assessment. Since experimental results on spatial cross-sectional area loss of corroded steel and bond strength between concrete and corrosion product and between corrosion product and uncorroded rebar are still scarce [19–22], model error associated with seismic capacity prediction is quite large. Further experimental and computational research is needed to develop the numerical model for the seismic fragility of corroded piers or bridges with scour-induced damage.

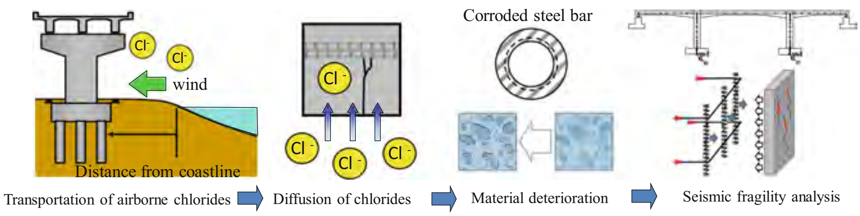


Fig. 10. Procedure of seismic fragility analysis considering effect of chloride-induced steel corrosion on deterioration of RC components.

Interacting Hazards

To estimate the reliability of structures under both seismic and tsunami hazards, or mainshock and aftershock as an example of interacting hazards, the structural vulnerability to the subsequent action needs to be evaluated considering the effects of ground motion-induced damage on the reduction of structural capacity. Figure 11 shows a damage sequence of piers subjected to earthquake excitation and subsequent tsunami. The residual displacement and the stiffness and strength degradation due to the ground motion are considered as the initial conditions when performing the pushover analyses to develop the fragility curves. Bridges become more vulnerable to tsunami due to ground motion-induced damage [13, 23].

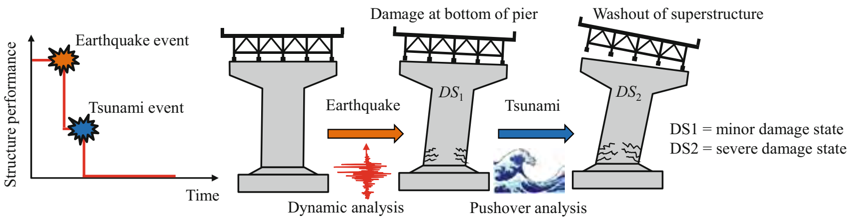


Fig. 11. Damage process of piers subjected to earthquake excitation and subsequent tsunami.

Climate Change Effects

In the wake of recent catastrophes exacerbated by climate change effects, the impact of climate change on civil infrastructure has received increasing attention around the world. For hazards intensified by the effects of climate change, predicting future conditions is significantly complicated because future climate data derived from general circulation models (i.e., GCMs), such as future temperature and precipitation, cannot be easily related to structural demand and capacity under future hazards. The lack of reliable climate models means that previous studies cannot adequately quantify the increasing risk to civil infrastructure under the impact of climate change.

By comparing risk and resilience with and without climate change, the threat can be quantified. Figure 12 illustrates a schematic approach for estimating the reliability, risk, and resilience of bridges. This framework requires individual techniques such as hydrological modeling using geographic information, reliability assessment of bridges under flood and scour hazards considering climate change, impact of higher temperature, humidity and CO_2 concentration effects on the deterioration of concrete structures, and functionality loss assessment of road network. In addition, the issue of climate non-stationarity and its impact on climate loads, load combinations, and structural reliability should be addressed.

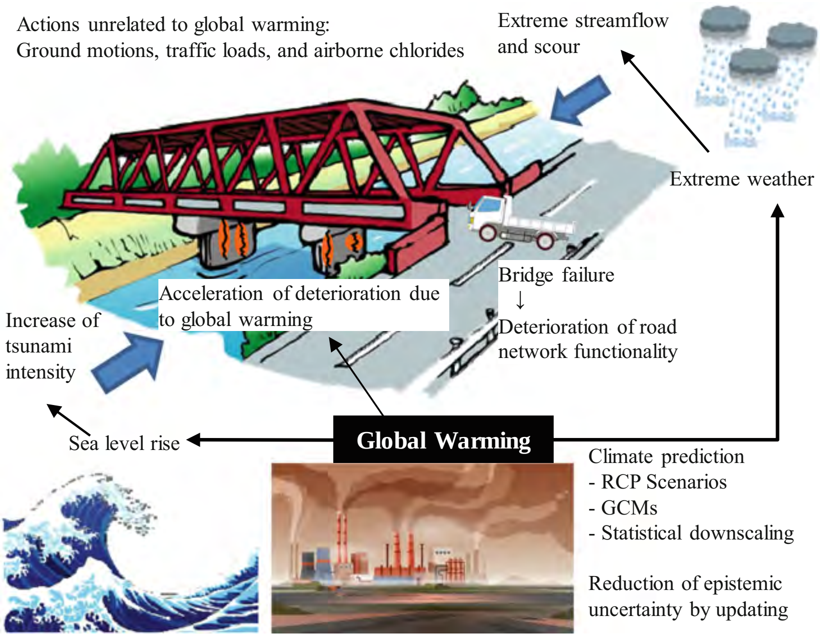
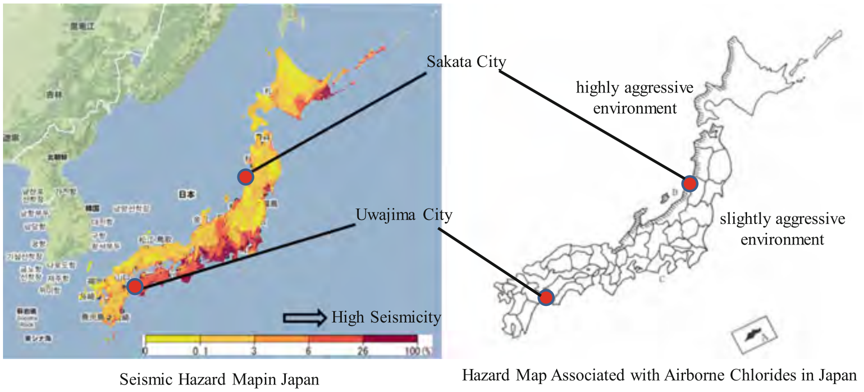


Fig. 12. Structures and infrastructure systems exposed to multiple hazards and climante change

4 Illustrative Examples

Several case studies presented in the literature by the authors and their co-workers are introduced herein to illustrate how to ensure life-cycle reliability, risk, and resilience of bridges and bridge networks under multiple hazards and climate change impacts.

Figure 13 shows the relationship between the cumulative-time failure probability and the time after construction of bridge piers in Sakata and Uwajima Cities [13]. To investigate the effect of corrosion on the failure probability, the cumulative-time failure probabilities without deterioration are also shown in Fig. 13. The geometry and structural details of the RC bridge pier in the two cities are the same. Initially, the failure probability of the bridge piers depends only on the seismic hazard, and the RC bridge pier located in Uwajima City has the higher failure probability. However, the probability of exceeding a prescribed amount of airborne chloride in Sakata City is much higher. The cumulative-time failure probability of the RC bridge pier in Sakata City increases with time due to chloride attack. The difference between the cumulative-time failure probability associated with both seismic and airborne chloride hazards and that associated with seismic hazard alone is greater for Sakata City. Finally, at 50 years after construction, the cumulative-time failure probability of the RC bridge pier in Sakata City is higher, even though the seismicity in Sakata City is lower than that in Uwajima City. To ensure the seismic reliability for the entire lifetime of the RC bridge pier in a marine environment, it is extremely important to consider the effect of corrosion on the seismic capacity and demand.



City	Seismic Environment	Marine Environment
Sakata	Mild	Severe
Uwajima	Severe	Mild

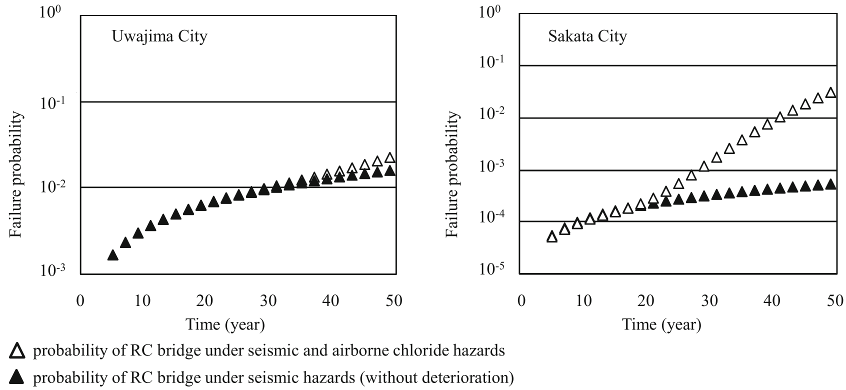


Fig. 13. Life-cycle reliability of RC bridge piers under seismic and airborne chloride hazards in case of Uwajima and Sakata Cities [13].

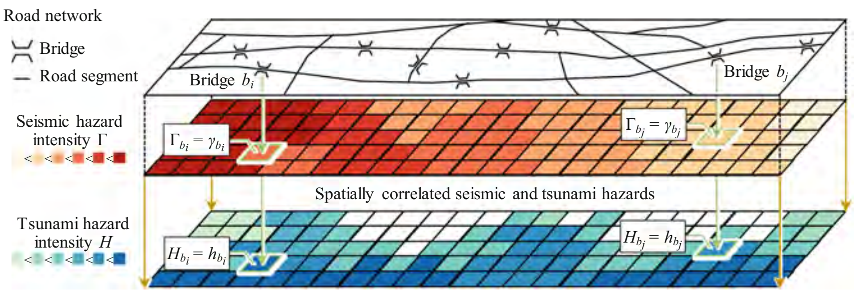


Fig. 14. Spatially correlated seismic and tsunami hazards [24].

When assessing the probabilistic connectivity of a large road network exposed to both ground motion and tsunami, it is important to consider the spatial correlations between hazard intensities, as shown in Fig. 14 [24]. To evaluate the joint probabilities of bridge states (i.e., passable and impassable states) and the probabilistic connectivity of road networks, the total probability theorem is used to integrate spatially correlated seismic and tsunami hazard assessments into the fragility estimates that consider the cascading effects of ground motion- and tsunami-induced damage to bridges.

As discussed in Sect. 2, the amount of disaster waste is one of the most important performance indicators for quantifying a community's resilience. Disaster waste can have a significant negative impact on the environment in the affected regions and hinder the post-disaster recovery process. Adequate disaster waste management should be developed in Japan prior to the occurrence of the Nankai Trough earthquake. The seismic and tsunami intensities caused by the anticipated Nankai Trough earthquake are expected to be significantly greater than those caused by the 2011 Great East Japan earthquake. Figure 15 illustrates the risk curves associated with disaster waste from buildings collapsed by ground motion and tsunami due to the anticipated Nankai Trough earthquake [10]. The risk of disaster waste depends on the number and location of structures and the intensity of the earthquake and tsunami. In the areas, such as Kuwana City, where the tsunami inundation depth is negligible, the risk curve is determined by the seismic effect only. Meanwhile, in the areas such as Owase City where the tsunami hazard is severe, the amount of disaster waste is underestimated if the effects of both seismic and tsunami impacts are not considered.

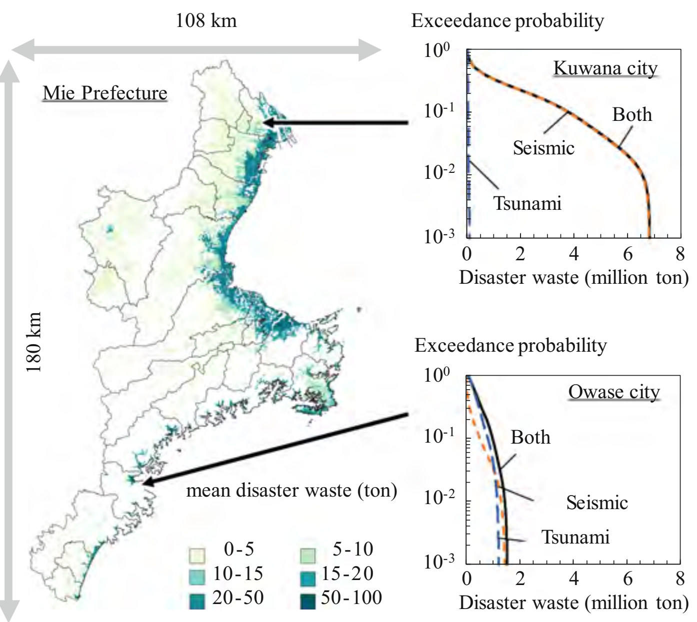


Fig. 15. Risk curves associated with disaster waste of buildings collapsed by ground motion and tsunami due to the anticipated Nankai Trough earthquake [10]

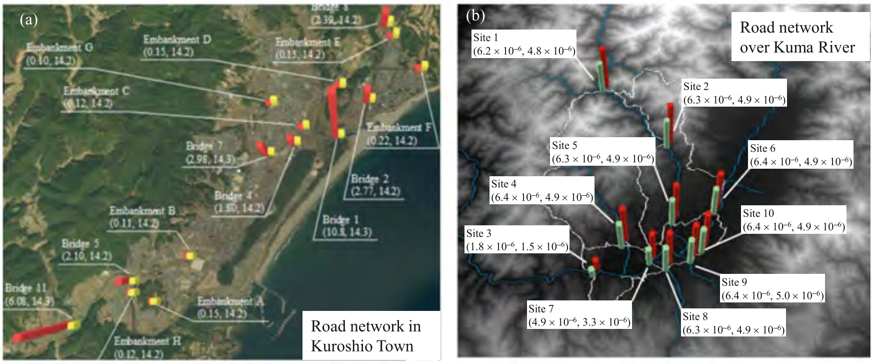


Fig. 16. Example of retrofitting prioritization of bridges in a road network (a) under seismic and tsunami hazards; and (b) seismic and flood hazards

The results of this case study show that a large amount of disaster waste would be generated in Mie Prefecture by the Nankai Trough earthquake with a high exceedance probability. Countermeasures to strengthen disposal capacity and facilitate cooperation with other prefectures before the event are important to reduce the adverse effects of disaster waste.

Under budget constraints, it is important to efficiently identify bridges that should be retrofitted. When they are exposed to multiple hazards, this process becomes more complicated. There are several performance indicators that can be used to prioritize retrofitting, including the reliability of individual bridges, the probabilistic connectivity of a road network, and risk and resilience considering the corresponding consequences. Figures 16(a) and (b) shows an example of performance indicator calculations to prioritize bridges in a road network under seismic and tsunami hazards as the interacting hazards [23], and under seismic and flood hazards as the independent hazards [25], respectively.

Climate change and the resulting more extreme weather events are likely to impact structural performance. This phenomenon can pose direct threats to infrastructure systems, as well as significant indirect impacts on those who rely on the services these assets provide. Such threats are path- and location-dependent, as they are highly dependent on current and future climate variability, location, asset design life, function, and condition [26]. Framework for probabilistic tsunami hazard assessment considering the effects of sea-level rise due to climate change was presented in [27]. It was applied to a region where the ground motion and tsunami intensities would be extremely large during the anticipated Nankai Trough earthquake [28–30]. Figure 17 shows an example of tsunami inundation maps without and with sea-level rise [29].

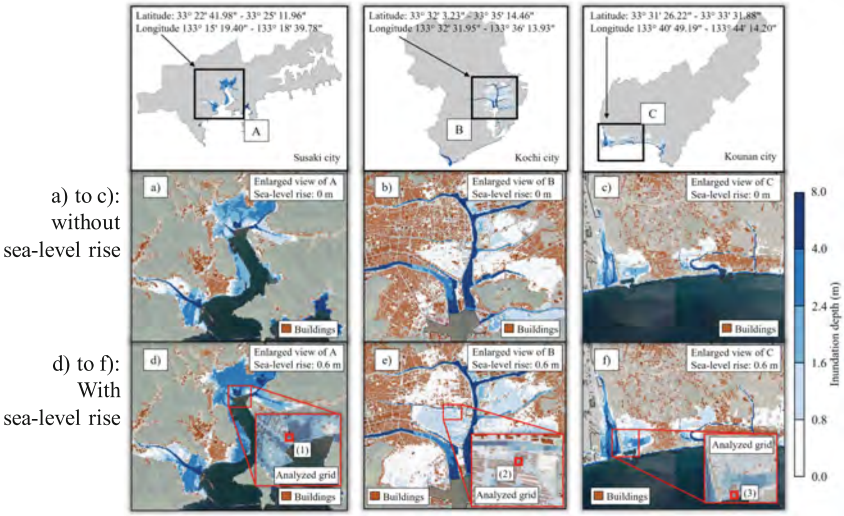


Fig. 17. Tsunami inundation maps without/with sea-level rise [29]

5 Conclusions

In the aftermath of a catastrophic event, the functionality of individual and spatially distributed structures such as transportation networks can be significantly degraded, resulting in catastrophic economic impacts. The concept of resilience is needed to quantify the time required for recovery. In addition, the economic, environmental, and social impacts of disaster waste management systems need to be studied in terms of sustainability. Consequences related to resilience and sustainability need to be investigated and implemented in the risk assessment of the bridge network under multiple hazards. The life-cycle design and assessment methodology can incorporate all the key concepts such as risk, resilience, sustainability, and multiple hazards, learning from the lessons of past disasters.

Finally, the concepts and methods presented were illustrated on both single bridges and bridge networks with emphasis on earthquake, tsunami, flooding, and continuous deterioration in addition to climate change. A risk-based decision-making approach at the network level is required to identify the dominant hazard and the vulnerable structures that require strengthening and retrofitting.

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Reliability and Durability of Built Environment Under Impact of Climate Natural Hazards

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Abstract. Constructions should be able to remain stable for their designed lifetime, from 50 to 100 years, even more. As climate change intensifies, extreme weather events such as temperature variation, humidity, heavy rainfall, floods, and windstorms become more frequent and more severe. These events pose a significant threat to conventional building designs and infrastructures. Consequently, there is a growing demand for climate-resilient constructions that can withstand extreme weather conditions. Protecting infrastructure and buildings to cope with these threats is a complex challenge. Building materials, design, and construction techniques need to be adapted to ensure the durability and safety of structures in the face of changing climatic conditions. The safety margins and robustness of constructions for undesired events in technical regulations and standards should therefore be continuously re-evaluated so that the designed level of reliability is maintained. To control by design, alternatively to traditional prescriptive design codes, where the building must conform to a set of given requirements that results in a hard-to-quantify performance, a Performance-Based Design (PBD) method might apply to explicitly define and achieve the desired structural performance. Based on the review and analysis of dedicated literature and research reports related to this complex problem, potential technical solutions are discussed. Also, two real study cases, one caused by extreme wind and the other by extreme drifted snow, are presented.

Keywords: Climate change · built environment · sustainability · extreme loading

1 Introduction

According to the definition adopted by the United Nations Office for Disaster Risk Reduction UNISDR (www.undrr.org), a hazard is a potentially damaging physical event or phenomenon that may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation. Hazards can have different origins:

– natural (earthquakes, floods, strong winds, snowstorms, …);
– human-made (environmental degradation, technological accidents, intentional attacks, …).

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When becomes extreme, such events can have a dramatic impact on the communities, causing more and more economic and human losses each year. Structural design is often governed by climatic related actions, e.g., wind or snow. As a consequence, variations of climatic actions (intensity, frequency) due to climate change could significantly affect the design of new structures and infrastructures, as well as the safety of the existing ones, which were designed in accordance with the provisions of current or past codes [1, 2]. However, the existence of a hazard is not synonym with disaster. Generally speaking, disasters normally occur when hazard meets with vulnerability (vulnerable people, vulnerable assets – buildings, bridges, or vulnerable communities). Vulnerability can be increased or decreased by the degree of exposure (presence in the exposed areas). The potential for consequences, or risk, is often represented as a probability of occurrence of hazardous events multiplied by the impacts if these events occur. The risk is the result of the interaction between vulnerability, exposure, and hazard, see Fig. 1. The response to these challenges is now seen in sustainable development, which should also integrate the adaptation and mitigation responses (or AMSD) [3–5].

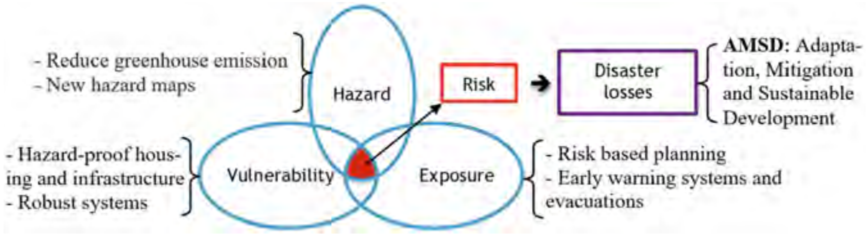


Fig. 1. Disaster risk and its dimensions: vulnerability, exposure and hazard, and consequence of risk (losses) (adapted from [5]).

According to whc.unesco.org, climate change poses significant physical, social and cultural risks on cultural heritage, but this can be extended to all built environments. To identify the greatest global Climate Change risks and impacts on built environments, the scientific community uses the climate parameters tabulated in Table 1 (only a selection is included) [6].

It should be stressed also that the design lifetime of structures, which is recommended to be at least 50 years for buildings [7], should not be confused with the real life of structures, which can be much longer. As a result, buildings are expected to be more affected by climate change. The implications of climate change on existing buildings as well as on new constructions is a key aspect in the development of second generation of Eurocodes [8]. At national levels and EU levels, additional efforts are in progress, with attention on both short-medium but also long-term objectives, e.g.:

– the National Strategy and National Action Plan for Adaptation to Climate Change, 2022–2030 (SNASC and PNASC), and the National Strategy and National Plan on Romania's contribution to the EGD's emission targets ([9]);
– National Strategy for the Sustainable Development of Romania 2030 (SNDDR 2030) [10];
– Romania's recovery and resilience plan PNRR [11];

– Disaster Risk Reduction Strategy for Romania PNMRD [12]
– EU strategy on adaptation to climate change [13].

Table 1. Principal Climate Change risks and impacts on cultural heritage (adapted from whc.unesco.org).

Climate indicator	Climate change risk	Physical, social and cultural impacts on cultural heritage
Atmospheric moisture change	– Flooding (sea, river) – Intense rainfall – Changes in water table levels – Changes in soil chemistry – Ground water changes – Changes in humidity cycles – Increase in time of wetness – Sea salt chlorides	– Physical changes to porous building materials and finishes due to rising damp – Damage due to faulty or inadequate water disposal systems – Erosion of inorganic and organic materials due to flood waters – Biological attack of organic materials by insects, moulds, fungi, invasive species such as termites – Subsoil instability, ground heave and subsidence – Relative humidity cycles/shock causing splitting, cracking, flaking and dusting of materials and surfaces – Corrosion of metals

(*continued*)

Table 1. (*continued*)

Climate indicator	Climate change risk	Physical, social and cultural impacts on cultural heritage
Temperature change	– Diurnal, seasonal, extreme events (heat waves, snow loading) – Changes in freeze-thaw and ice storms, and increase in wet frost	– Deterioration of facades due to thermal stress – Freeze-thaw/frost damage – Damage inside brick, stone, ceramics that has got wet and frozen within material before drying – Biochemical deterioration – Changes in 'fitness for purpose' of some structures. For example, overheating of the interior of buildings can lead to inappropriate alterations to the historic fabric due to the introduction of engineered solutions – Inappropriate adaptation to allow structures to remain in use
Wind	– Wind-driven rain – Wind-transported salt – Wind-driven sand – Winds, gusts and changes in direction	– Penetrative moisture into porous cultural heritage materials – Static and dynamic loading of historic or archaeological structures – Structural damage and collapse – Deterioration of surfaces due to erosion
Climate and pollution acting together	– pH precipitation – Changes in deposition of pollutants	– Stone recession by dissolution of carbonates – Blackening of materials – Corrosion of metals – Influence of bio-colonialisation

(*continued*)

Table 1. (*continued*)

Climate indicator	Climate change risk	Physical, social and cultural impacts on cultural heritage
Climate and biological effects	– Proliferation of invasive species – Spread of existing and new species of insects	– Collapse of structural timber and timber finishes – Changes in appearance of landscapes – Transformation of communities

Most parts of Europe regularly endure severe weather events, like damaging winds, floods, or heavy snowfalls. Between 1980 and 2016, climate-related losses among EU Member States amounted a total of EUR 410 billion. The loss of human life, cultural heritage or ecosystem services is not part of the estimation. In the EU, the most expensive climate extremes in the same period include the 2002 flood in Central Europe (over EUR 20 billion), the 2003 drought and heat wave (almost EUR 15 billion), and the 1999 winter storm and October 2000 flood in Italy and France (EUR 13 billion), all at 2016 values [14].

In May 2014, cyclone Yvette affected southeast Europe, causing floods and landslides (Fig. 2).

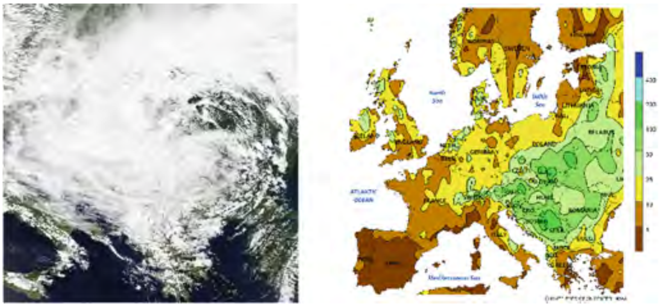


Fig. 2. Cyclone Yvette, May 11–17, 2014: satellite image (left) and the total precipitation in mm, computer generated contours (right).

The most affected countries were Serbia and Bosnia and Herzegovina, as the rain was the heaviest in 120 years of recorded weather measurements. At least 62 people had died because of the flooding; hundreds of thousands had to leave their homes, more than 1.6 million people affected. Assessments of the damage ranged up to 3.5 billion €. Eastern Croatia and southern Romania also experienced flooding and human losses. The events initiated a large international aid campaign in support for the affected areas. Less than 2 years later, the 2015–16 Great Britain and Ireland floods caused more than 5.2 bn £ in damages and forced the authorities to ask for a "complete rethink" of the national flood defence system. Heavy snowfalls and drifting from high winds, or ice accumulation might also cause severe structural accidents and significant losses (see winter 2005/2006; Kyrill storm, 2007; winter 2009/2010; November 2012, Taranto, Italy; 16–18 January 2017 in Balkan peninsula, locally with snowfalls of over 1 m and Bora winds gusting at 140–170 km/h). Influence of climate change on these extreme weather events has been well established.

Europe has also a long history of destructive earthquakes (Balkan and Mediterranean countries are all at high seismic risk) (more 110 billion EURO losses in EU Member States between 1980 and 2016) (Fig. 3). Even of moderate intensities, earthquakes can lead to disasters when hit vulnerable buildings or infrastructures. For example, the 6.3-magnitude quake that struck Italy in 2009 killed 308 people and caused more than $4 billion in direct damages and an estimated $16 billion for rebuilding. One possible cause of such devastation was the small epicentral distance (near-field earthquake), which caused very large vertical accelerations. The quake left behind also many controversies regarding the handling of the disaster.

Sources of risk may also come from human activities, i.e. natural gas extraction. Such hazards put the infrastructure at high risk especially in non-seismic or very low seismic areas because the current building stock is not designed and detailed to withstand seismic actions. Even seismic events are very damaging natural events, the seismic design principles and additional structural demands make the structures generally less vulnerable to other hazards.

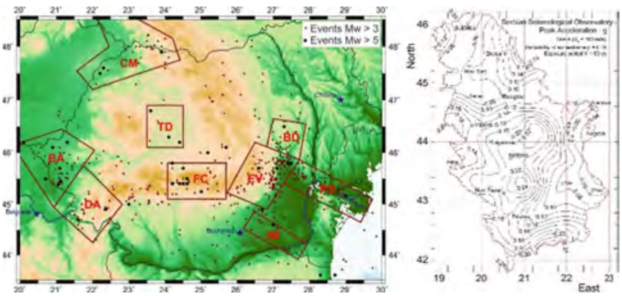


Fig. 3. Normal depth seismicity (h < 60 km) in the Banat region (www.infp.ro/en/) (left) and preliminary map of peak accelerations (g), for a probability of 5% exceedance and an exposure period of Y = 50 years (www.seismo.gov.rs/).

Such disasters can lead to malfunction of vital services and the recovery may take days, weeks or even longer time. The society is relatively resistant to short duration emergencies; however, it is vulnerable to long-term emergency states that often lead to a social disintegration. As a result, a strategic goal of the Hyogo Framework for Action HFA, 2005–2015 (www.undrr.org) was “the development and strengthening of institutions, mechanisms and capacities at all levels, in particular at the community level, that can systematically contribute to building resilience to hazards”. For harmonization and track of progress among partner countries, UNISDR instituted a systematic process of national reporting, accompanied by reporting on progress on the implementation of the HFA. Overall, the HFA has provided critical guidance in efforts to reduce disaster risk and has contributed to the progress towards the achievement of the goals. Its implementation has, however, highlighted a number of gaps in addressing the risk factors, formulation of goals and priorities, so that at the end of the Action, disasters continued to undermine efforts to achieve sustainable development. The Sendai Framework (S), the successor of HFA, entered in action in 2015 and was set to end in 2030. The Sendai Framework for Disaster Risk Reduction and the Sustainable Development Goals (SDGs) are built on elements which ensure continuity with the work done in HFA, but introduces several innovations:

- the shift from disaster management to disaster risk management.
- the definition of main global targets.
- more focus on preventing new risk, reducing existing risk and strengthening resilience.
- set of guiding principles, including primary responsibility of states to prevent and reduce disaster risk, all-of-society and all-of-State institutions engagement.

In addition, the scope of disaster risk reduction has been broadened significantly to focus on both natural and human-made hazards and related environmental, technological and biological hazards and risk.

In the next sections, two case study projects are detailed. In the first case, a robust structure suffered serios damages but remained standing even loaded by an extreme drifted snow. In the second case, a strong wind intensified locally and partially destroyed the light steel-based roofing system of a warehouse building. Apart from property losses, the accident put at serios risk the people inside the building. In both cases, damage was assessed, and retrofitting interventions were proposed to reduce the susceptibility to similar damages in the future.

2 Case Study: Large Span Steel Frame Production Unit Exposed to Extreme Drifted Snow

2.1 Building Description

The case study building structure is a 78 m wide and 180 m long building, with an eave height of 8.0 m and destination production (see Fig. 4, Fig. 5a). On transversal direction, the intermediate spans are: one of 15 m, two of 24 m and two of 7.5 m (see Fig. 5a). Last two spans are with an intermediate floor (mezzanine). The roof was made from 100 mm thick sandwich panels, supported by Z cold formed purlins with 2.0 mm thickness, and arranged as continuous elements with overlapping on the supports. On the first and last bay the purlins were strengthen using additional Z section elements (with same properties). The purlins were connected to the transversal steel beams using steel studs and 3 M12 bolts, grade 8.8. Adjacent to the case study building end, there is another building, 72 m wide and 120 m long (see Fig. 4, Fig. 5b). This adjacent building is 4.0 m taller, i.e., the height is 12.0 m (see Fig. 4 right, Fig. 5c).

The two buildings were completed in 2004 and put into operation in the same year. The two buildings are located in the outskirt of the Romanian capital, the Bucharest city. The site is characterized by a high seismicity, i.e., 0.20 g (at the time of construction) and moderate snow falls, i.e., the characteristic value of the uniform snow load on the ground

Fig. 4. Photos with case study building (difference in height between production unit and warehouse is visible in the right photo).

of 1.2 kN/m^2 (at the time of construction). The design code at the time of construction allowed also to consider a drifted snow due to difference in height between adjacent buildings by means of μ_2 factor (see [15]), but this was limited to $\mu_2 = 2.0$. Any value beyond this limit would require the classification of snow as accidental, and eventually leading to smaller load intensity.

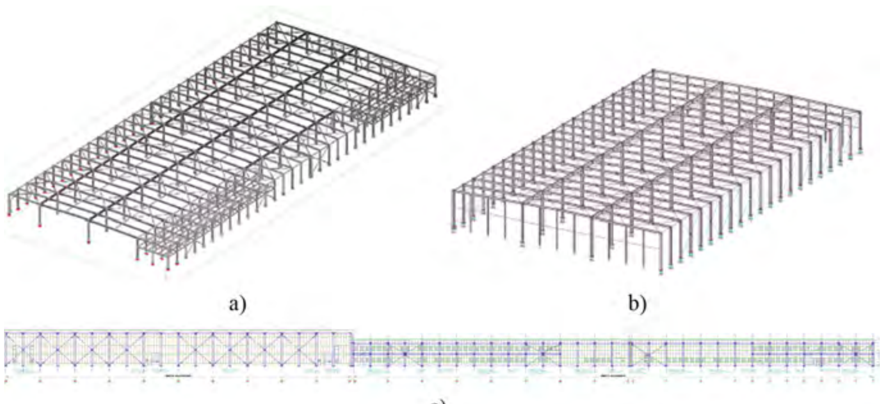


Fig. 5. Geometry of the case study building: a) 3D view of case study building; b) 3D view of adjacent taller building (warehouse); c) side view, with lower height case study building on the right.

2.2 Heavy Snowfall and Damage to the Building

Following a heavy snowfall in February 2010, the snow piled up on the roof due to strong wind, until eventually filled the difference in height between the two buildings (approximately 4.5 m thick at maximum). The drift length of the snow accumulation amounted approximately 7.0 m, while the average snow depth on the rest of the roof was approximately 1.0–1.1 m (Fig. 6). Same snow load was also measured on the taller unit (warehouse building).

The snow accumulated on the roof in the first bay caused extensive plastic deformations in the roof sandwich panels, and partial failure of the purlins due to lateral torsional buckling (Fig. 7). The purlins have not lost however the continuity at overlapping and resisted without complete failure. For safety reasons, the operator decided to improvise some props for the roof in order to save it from collapse. At the same time, an operation to remove the snow in the most affected areas commenced. Main transversal beams suffered also significant deformations, with some torsional deformations of the cross section most visible at midspan.

After the complete removal of the snow, a temporary strengthening solution was proposed, with additional purlins on the last span. Even heavily deformed, the sandwich panels partially recovered the initial position and were temporarily in position. Then, a complete structural assessment was done, which also included the main transversal beams and their connections to the columns. To prevent any damage from future large snow loads, the new roof system used same purlin typologies but placed at much smaller spaces and stronger end connections. New sandwich panels were also mounted.

Due to the increase of the seismic intensity between the date of completion and the date of assessment (see Fig. 8), some interventions were also necessary to the lateral load system, mainly the vertical X braces. Bolts in the most affected connections of the transversal main beams were also replaced with new ones.

Fig. 6. Snow accumulated at the contact between the two buildings.

Fig. 7. Sandwich panels and purlins propped by wooden pallets.

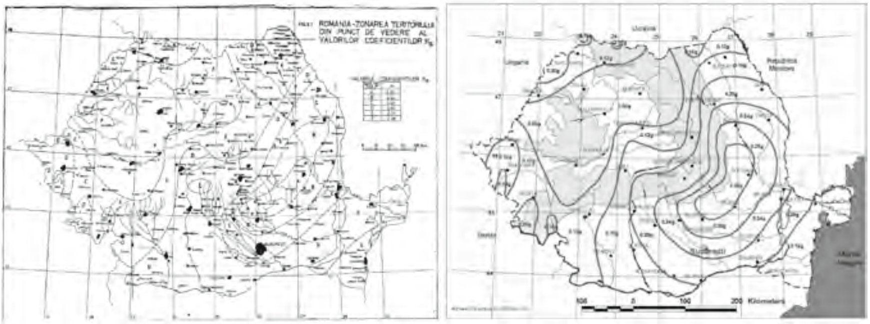


Fig. 8. Map of horizontal peak ground acceleration for Romania (for Bucharest, $a_g = 0.20g$ in 2004 (left), and $a_g = 0.24g$ in 2010 (right).

2.3 Numerical Simulation of the Accidental Snow Load Effects on the Roof

The numerical simulations were done using the software SAP2000 [16]. To reduce the numerical computation demand, the model included 2 purlins and the supporting main beams, see Fig. 9a, b. The purlins were extended in the second span until the approximative position of the inflexion point, i.e., 1.2 m, which was considered pinned. The sandwich panels have been also included in the model, but only to apply the distributed loads and provide partial lateral restraints to the top flange of the purlins. The purlins were connected to the studs attached to the beams using 3 fasteners, see Fig. 9c. The rigid contact between the purlin bottom flange and supporting beam was also modeled using gap elements, see Fig. 9c. The supporting beams were considered fixed at both ends.

The load was applied by pushing down the panels until purlins' failure; this was done using displacement control. Nonlinear shells were used to mesh the purlins and the supporting beams, see Fig. 9b. The properties of the steel, including the yield strength (f_y), the total ultimate strain (A_t) and the corresponding strength at fracture, (f_u) were based on the nominal properties, i.e., S355 grade for supporting beams ($f_y = 355$ MPa) and hot dip galvanized FeE320 G for the purlins ($f_y = 320$ MPa). The behavior of the end fastenings was modelled using link elements connecting the purlin web to the studs fixed on the beams, see Fig. 9c. The link behavior was characterized using a multilinear plastic law on x and y direction, and the maximum shear capacity was calculated using [17]. The directional properties on z were considered fixed.

Figure 10 compares the numerical load - displacement curve and the design loads used in the original design, i.e., design uniformly distributed snow (UDL) and the design patterned load (PL) that considers the snow deposited due to wind. The tributary area is 3.2 by 7.2 m. The actual snow load on the roof is also presented in Fig. 10, and is based on site measurements and an approximate characteristic weight of 2.5 kN/m^3. The increased characteristic weight is based on wheatear conditions on site at the time of snow fall, i.e., wet snow due to previous rains.

As can be seen, the purlins have the capacity to resist both UDL and PL, with some reserves when compared to peak flexural capacity. If the load continues to increase, purlins loss the stability and the capacity slightly decreases. The second increase in

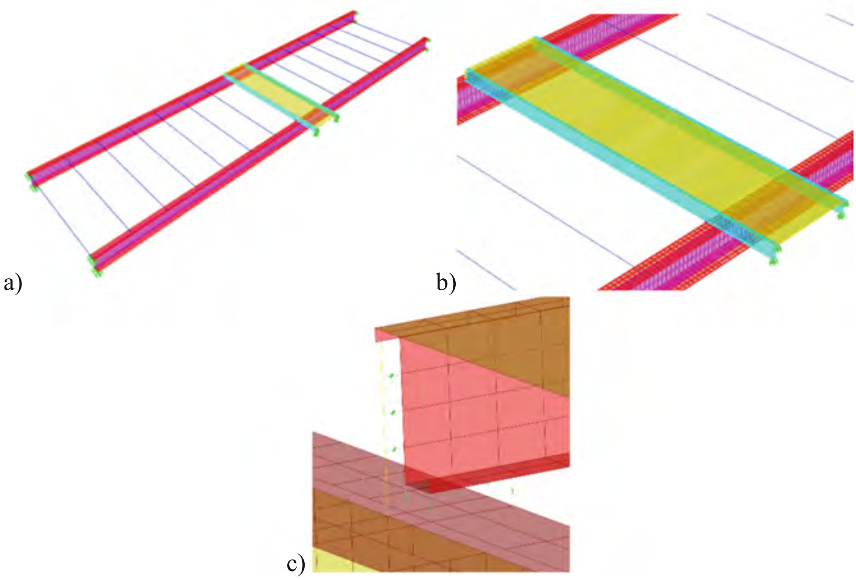


Fig. 9. Numerical model: a) global view of the model; b) detailed view with the wall mesh and end fastenings; c) purlin end connections and boundary elements.

capacity is due to the development of the catenary action in the purlins, even the cross section is rotated by almost 90º (Fig. 11). A second drop in capacity takes place right beyond the actual snow load (127 kN), and the purlins fail under a total load of 176 kN, due to the failure of the end fasteners. At the failure, the axial force in the purlins amounts 119 kN, see Fig. 12.

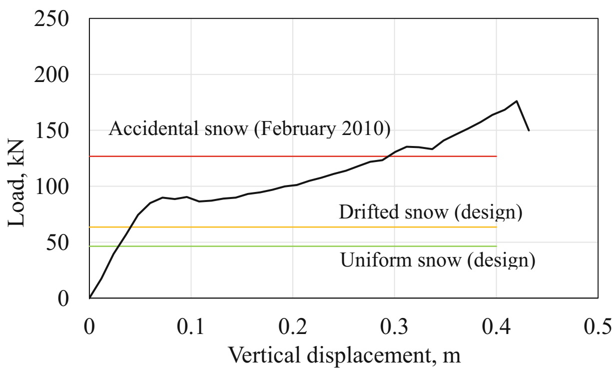


Fig. 10. Vertical load vs vertical displacement for a two purlins model (tributary area 3.2 × 7.2 m).

It is therefore important to note that purlins behave actually very good, with significant post flexural capacity due to catenary action. This however could create additional problems and lead to more severe damages and failures in the supporting beams.

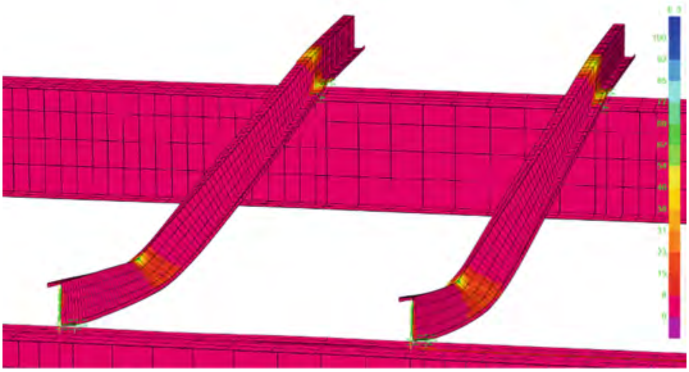


Fig. 11. Deformed shape and EVM strains in the two purlins (tributary area 3.2 × 7.2 m).

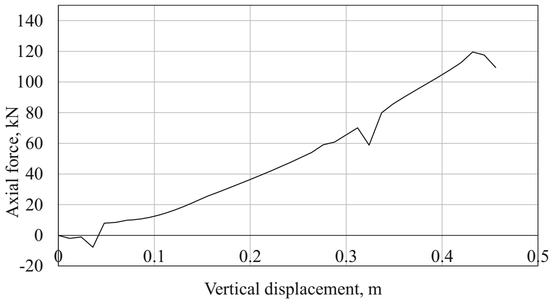


Fig. 12. Axial force in one purlin vs vertical displacement.

3 Case Study: Roofing of Large Span Concrete Frame Industrial Building Exposed to Extreme Wind

3.1 Building Description

The case study building is a single-story warehouse building, with main structure of prefabricated concrete elements, with plan dimensions of 97.42 m × 100.57 m; height at the eaves 13.6 m (see Fig. 13). The roof is made with sandwich panels KINGSPAN, with support made of corrugated sheet, supported by prefabricated prestressed concrete purlins (see Fig. 14).

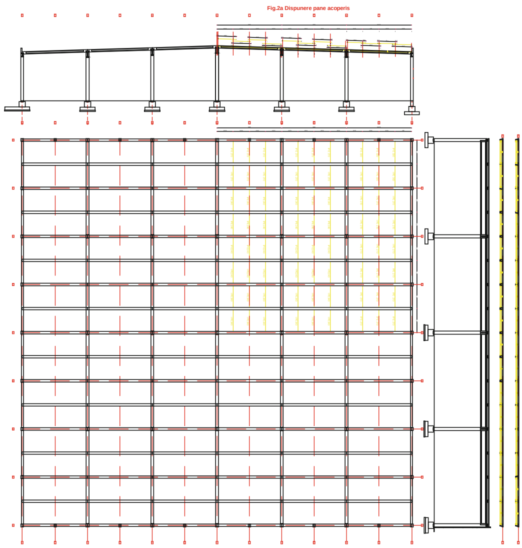
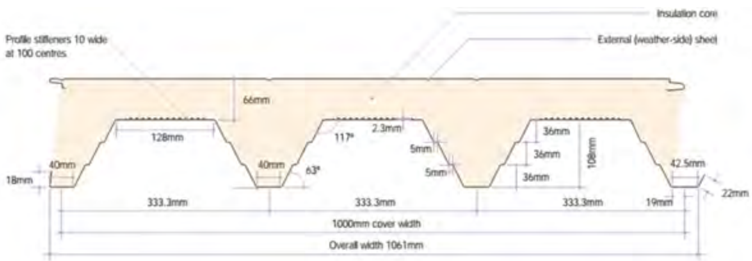
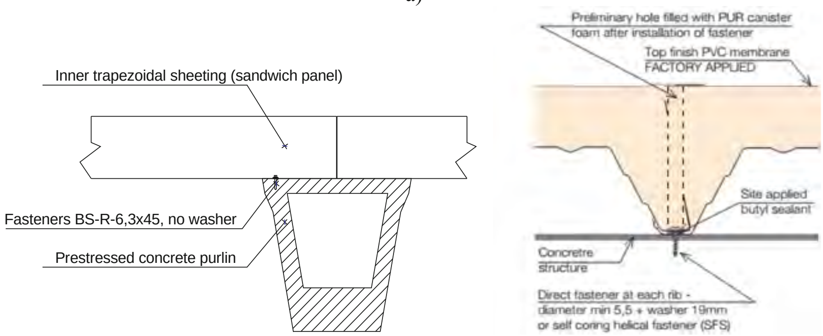


Fig. 13. Geometry of the structure, with roof view and transversal/longitudinal frames.



a)



b)

Fig. 14. Details of the purlins and roof to purlin connection: a) roof panels; b) detail with panel support on prestressed concrete purlins, transversal (left) and longitudinal (right).

3.2 Windstorm Damage to the Building Roofing and Enclosure Walls

During a strong windstorm in June 2017, the building suffered extensive damage at the level of the roof and enclosure walls (Fig. 15). According to the data recorded at a nearby weather station, the wind speed exceeded 20 m/s, and wind gusts of 35 m/s. Using footages from inside surveillance cameras, the sequence of failure was (1) removal of the roof panels due to strong uplift forces (under pressure), followed by sudden removal of one large side door due to wind pressure. The observations made after the event revealed that panels' removal was caused by both fasteners' pullover and/or pullout. On some roof areas, the sandwich panels remained attached to the purlins, but the outer cladding has been ripped out, leaving the insulation core exposed (Fig. 15).

Following the accident, an extensive structural assessment was performed, which looked both at finding the causes of damage, but also to provide a strengthening solution for the vulnerable components. Also, laboratory tests were performed on similar sandwich panels and connecting details (panel to concrete purlin) to find out the chain of failure and provide improved solutions. The main findings were the following:

– the uplift forces due to wind on most exposed roof areas (noted with F, G, see Fig. 16) obtained from data recorded at nearby weather station did not exceed the maximum design forces obtained from code [18]; also, location of damages provides information about roof areas with largest under pressures (areas were uplift forces are at maximum);
– the laboratory testing revealed actual capacities of fasteners smaller than the design values provided by the supplier. The exceedance was nearly 100%, when the washer is not present. Also, due to thin concrete webs of the hollow prestressed concrete purlins, the fastener capacity is further reduced when fixation is too close to the edge (see Fig. 14c).
– retrofitting of the remaining roof area and strengthening the fastening would be technically difficult. Instead, additional intermediate purlins were proposed, which help distributing the uplift forces to more fasteners, and thus reduce the vulnerability to further similar events (Fig. 17).

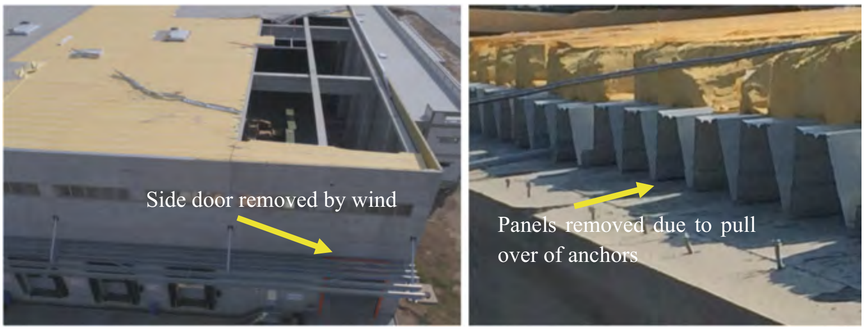


Fig. 15. Roof (and side door) destroyed by wind: a) aerial view with the damaged roof; b) detail with end support fasteners in the affected roof area.

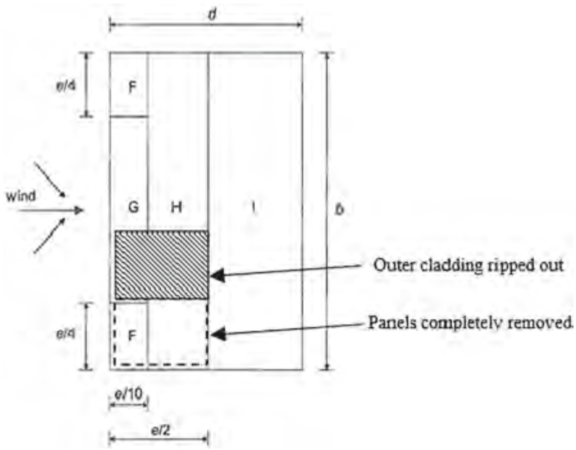


Fig. 16. Key for flat roofs (see [18]) and roof areas damaged by wind marked with dashed line (panels removed) and hatches (outer cladding ripped out).

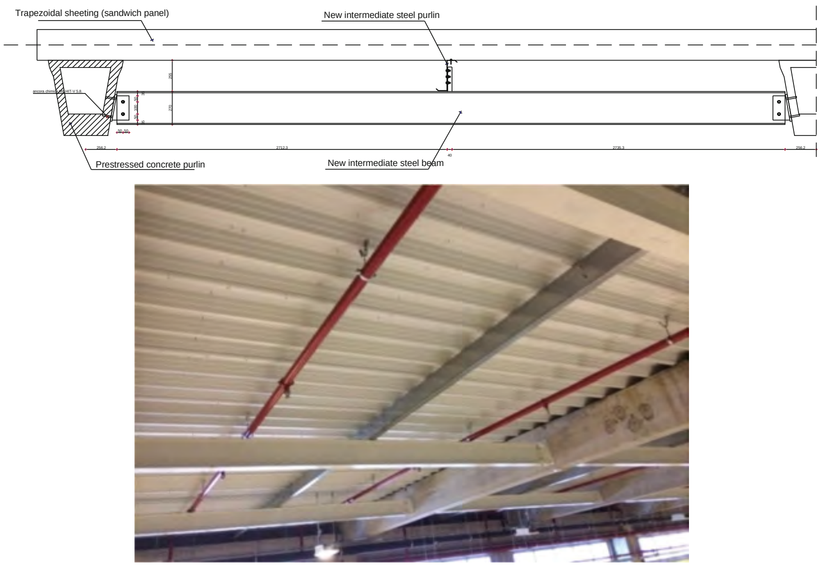


Fig. 17. Retrofitting intervention for roof, with new intermediate secondary IPE steel beams fixed between two concrete purlins and Z steel purlins (top) and photo after completion (bottom).

4 Conclusions

Constructions should be able to remain stable for their designed lifetime. Scenarios for future changes in temperature, relative humidity, levels of precipitation, wind speeds associated with gust effects, and frequency of extreme weather events should be studied today to make possibly evaluation, control, adapt and or minimize their impacts on the built environment. The return periods of weather events may change, too. The safety margins and robustness of constructions for undesired events in technical regulations and standards should therefore be continuously re-evaluated so that the designed level of reliability is maintained.

Despite the growing understanding and acceptance of the importance of disaster risk reduction and increased disaster response capacities, natural disasters continue to pose a global challenge. As climate change intensifies, extreme weather events such as heavy rainfall, floods, windstorms, and snowfalls become more frequent and more severe. These events pose a significant threat to conventional building designs and infrastructures. Consequently, there is a growing demand for climate-resilient constructions that can withstand extreme weather conditions, all at affordable costs. The effects of climate change on existing buildings as well as on new constructions is a key aspect in the development of second generation of Eurocodes. At national levels and EU levels, additional efforts are in progress, with attention on both short-medium but also long-term objectives. Climate-resilient construction design philosophy should definitely include the adaptability concept.

The two real case studies presented in the paper, one caused by extreme wind and the other by extreme drifted snow, showed that extreme weather can be damaging, and not only in terms of economic costs, but also in terms of protecting the life of occupants. Even not specifically designed for such amount of snow, first example showed that continuity of the purlins and proper detailing of the roof system could prevent the extension of collapse, even there were significant damages. On the other hand, lack of robustness and lack of quality control can lead to a chain of local failure, disproportionate compared to the initial cause.

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Sustainable Infrastructures

Integration of Carbon Emissions Estimates into Climate Resilience Frameworks for Transport Asset Recovery

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Abstract. This study describes a framework for optimizing environmental sustainability, climate resilience, and cost in post-hazard transport asset recovery. Particular focus is given to the environmental impact assessment component and its conceptual integration with resilience metrics. After describing the workflow adopted in the complete framework, the environmental impact modelling assumptions, system boundaries, and life cycle inventories for materials, on-site activities and transportation are detailed. Carbon equivalent emissions are evaluated for various restoration tasks for a bridge subjected to nine flood scenarios and represented through a sustainability index. A baseline environmental impact analysis is initially conducted, considering conventional materials, construction techniques, and procedures for each restoration task. Additional sensitivity studies are carried out to evaluate the influence of low-carbon solutions and task duration on carbon emissions. These are weighted based on the probability of the bridge being in a specific damage state. The results demonstrate that low-carbon solutions can provide carbon savings to varying degrees depending on the hazard intensity. Normalised sustainability, resilience, and cost metrics are combined into a unique global index, which can be adopted to prioritise the recovery of the asset. Suggestions on adopting circularity indicators and waste hierarchy levels into such frameworks are also given.

Keywords: Sustainability · Climate Resilience · Circularity · Metrics · Transport

1 Introduction

The built environment consumes 50% of raw materials, contributing to 36% of global energy use and 39% of energy related CO_2e emissions [1]. Infrastructure assets are the backbone of a sustainable society, integrated into a system of systems. The smooth operation of these systems is essential for the functioning and development of society.

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Physical assets are increasingly vulnerable to various threats such as natural or man-made hazards, as well as prone to degradation from mechanical and/or environmental loading during service. Enhancing the resilience of such assets is instrumental to ensuring the continuity of essential services. Engineering resilience can be defined as the ability of an asset, or network, to withstand and restore swiftly from low-frequency high-impact events that change its capacity and function.

Sustainability is deeply ingrained in all aspects of infrastructure development and management. Evaluation of the performance metrics encompassing environmental, economic, and social considerations, have become integral for assessing the sustainability of the infrastructure assets and networks through their life cycle. In construction, the environmental component is typically considered through life cycle assessments (LCA) and is addressed below. Circularity involves transitioning from a conventional linear resource flow to a circular model. Restoration and regeneration represent a step forward, assuming a shift from an anthropocentric perspective to an eco-centric approach for a resilient environment. Restoration of physical assets requires resources, whilst restoration of the environment implies avoiding natural resources depletion.

This paper presents a case study describing the restoration of a transport infrastructure asset, specifically a bridge subjected to various flood scenarios, while considering sustainability and circularity. This is carried out through assessments of carbon emissions, resilience, and cost, as well as adoption of qualitative approaches for circularity.

2 Integrating Environmental Impact into Resilience Frameworks

This section summarises a framework that incorporates LCAs into climate resilience frameworks, through the global warming potential (GWP) category (in tCO_2e) and in a proposed a global metric (I_{SRC}). The global metric includes resilience, environmental sustainability, and cost. In this paper only a brief description of the framework, conceptual plots for sustainability and resilience, and the GWP assessments are described.

The conceptual plots depicted in Fig. 1 pertain to the scenario wherein a critical transport asset is impacted by a significant stressor, such as a flood, and appropriate measures are taken to reinstate its capacity and functionality. Figure 1 serves as an illustration of the benchmark case, while in Ref. [2], instances of ex-ante and ex-post restoration of well and poorly maintained assets are presented, respectively. Figure 1a shows the upfront (solid lines) and ancillary tCO_2e (dashed lines) resulting from the construction (as exemplified by paths OA) and maintenance of the asset throughout its lifespan. In all cases, the ancillary tCO_2e are demonstrated to exceed the upfront emissions due to the diversion of traffic during maintenance and restoration. Figure 1b, on the other hand, presents the resilience curves of the asset. The magnitude of resilience (R index) [3], denoted by the area under the resilience curve, is evaluated as a metric between the occurrence of the hazard event (t_e) and the completion of recovery at time t_h. Sustainability encompasses the entire lifespan of the asset.

With regard to characteristic points and paths the following definitions are considered in Fig. 1: O–construction starts, A–construction completed/asset operational, AB–bridge operates with minimal maintenance/inspection, A‘B’–greenhouse gasses (GHG) increase due to decrease in bridge functionality and traffic detours, BE–idle time due to no action taken post-hazard, B‘E’–GHG rapidly increase due to bridge closures and traffic diversion, EF–restoration measures are implemented, E‘F’–supplementary GHG due to restoration and traffic detour, FH–asset in normal operation, F‘H’–same as A‘B’. In Fig. 1b, the resilience has a small drop due to e.g., deterioration effects, which could be due to the corrosion of tendons and traffic increase. The gradual loss of bridge functionality may lead to occasional detours, and hence tCO2e, which are shown with line A‘B’ in Fig. 1a. The figure refers to the case where a hazard leads to a significant loss of asset performance, and a rapid increase in tCO2e between B‘E’ and at a smaller rate after the restoration of the bridge commences (point E in Fig. 1b). After the completion of the recovery, no additional direct tCO2e, and a small increase in indirect tCO2e (see F‘H’), similarly to A‘B’, occurs.

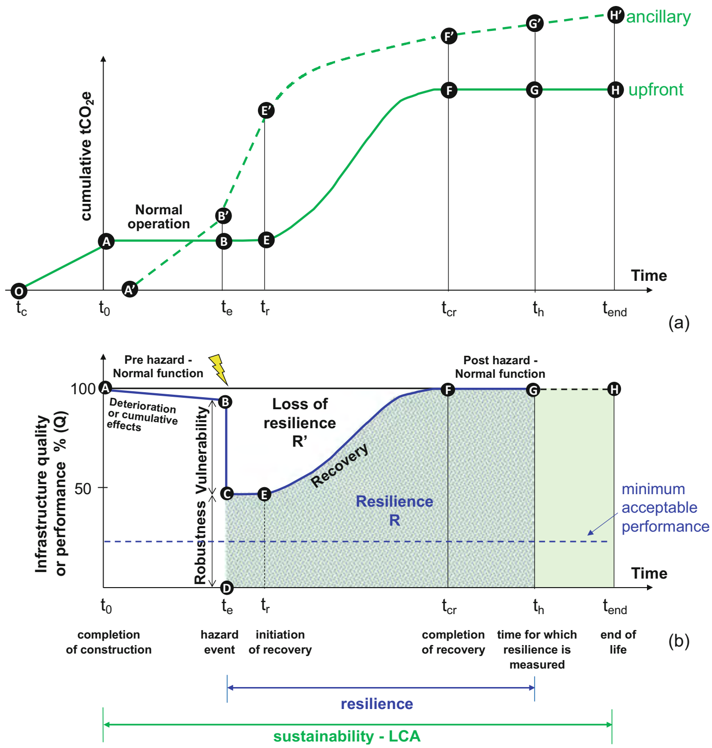

Fig. 1. Conceptual plots of sustainability and resilience for a baseline scenario without regular maintenance (a) evolution of GHG, and (b) resilience represented as the performance of transport asset responding to a hazard occurrence [2].

The framework includes the assessment of resilience, sustainability, and cost parameters in eight steps. First, (i) hazard intensity measures (IM) are defined based on predicted, measured, or estimated hazard data (e.g., high-resolution flood maps to deduce probabilistic relationships of established IM). These are then used to (ii) evaluate the vulnerability of the asset using fragility functions. The curves correlate the probability of exceeding given damage states (i.e. minor, moderate, extensive, severe/complete) with the hazard IM. After evaluating the fragility functions, (iii) the asset recovery is evaluated based on restoration (structural capacity) and reinstatement (traffic capacity) models. Subsequently, depending on the damage states, (iv) the GHG emissions are assessed using the procedures described in detail in this paper. The resilience (v) corresponding to the structural capability of the asset to withstand a hazard occurrence of different damage states for a given IM is then evaluated using a probabilistic approach. This is then transformed into a resilience index (R).

GHG emissions are evaluated for various restoration strategies and written in as relative measures in a sustainability index (S). For the latter, the cumulative tCO2e of the asset under recovery at a given time t after the start of restoration, are considered. The index considers the cumulative tCO2e of the asset under recovery and is weighted based on the probability of the asset being in a specific damage state and the temporal evolution of GHG per damage state. The latter depends on the emissions per restoration task (see details below). Finally, (vi-viii) the sustainability and resilience indices are optimised using a multi-criteria decision-making approach (e.g. Pareto fronts), and a cost index is evaluated afterwards. These are aggregated in the global metric (I_{SRC}) [2]. The framework and global metric are tested using a standard river crossing bridge that has three spans and is exposed to different flood scenarios [3–5].

3 Environmental Impact Assessments

3.1 Environmental Impact Modelling

Evaluation of the environmental impacts of a product or process, including production, transportation, and disposal, is typically conducted using life-cycle assessments (LCA) [6]. For civil engineering works, this is typically expressed in the Global Warming Impact (GWP) category through a carbon-equivalence tCO2e of all GHGs. Depending on the assessment method, the whole-life carbon is divided into embodied and operational components [6, 7]. Embodied carbon refers to the GHG incorporated in construction materials, processes, and activities [8]. Operational carbon refers to the GHG emissions during the service of a building or asset.

To evaluate the environmental impacts for the main restoration tasks, GWP measured in tCO2e was considered. The assessment includes GWP due to fossil emissions, as for construction works the biogenic emissions are insignificant, and can be disregarded. The system boundaries adopted here correspond to a 'cradle-to-practical completion' approach (A1–A5). The emissions are divided into the following groups: (i) the upfront emissions, correspond with the carbon for the works included in the restoration tasks at the stages shown below; and (ii) the ancillary emissions refer to traffic re-routing or pavement degradation, among others.

The data flows are assessed per restoration work and use established functional units for materials and processes, e.g., 1.0 m^3 for concrete or 1.0 kg for steel. These are subsequently converted into carbon emissions, based on the estimated bills of quantities and corresponding carbon equivalent factors listed in Table 1. The assumptions for estimating quantities and equipment use are in Sect. 3.2. The construction equipment fuel consumption rate is based on manufacturer datasheets. The emissions are assessed by multiplying the bill of quantities ($Q_{i,m}$) with the corresponding embodied carbon factor ($F_{i,m}$) and a scalar factor to account for the restoration task duration ($\lambda_f = 1$ for mean durations). The subscript i indicates the material or process, whilst subscript m is for the life-cycle phase (materials, onsite activities, or transport).

A baseline analysis is conducted first. This includes in-situ concrete with cement as the only binder and new reinforcing and prestressing rebars. The same strategies are analysed with low-carbon solutions to minimise emissions for carbon-intensive tasks. This reduction is achieved by replacing materials from virgin sources with low-carbon materials and using biofuel blends for construction equipment. The main conventional construction materials are substituted by low-carbon alternatives including fly ash and GGBS in concrete. Steel rebars and tendons contain 97% recycled steel obtained through electric arc furnace production. The baseline analysis assumes mineral diesel, while the low-carbon alternative assumes a biofuel blend. It is assumed that the transportation distance is 25 km and uses a diesel articulated HGV (>3.5 - 33t - average laden). Transporting people and construction equipment is not accounted for.

Table 1. Life cycle inventory.

Conversion factors	$kgCO_2e$/unit	Conversion factors	$kgCO_2e$/unit
Concrete C25/30 - CEM 1	0.142/kg	Fibreglass	1.540/kg
Concrete UK C25/30 (25% GGBS)	0.130/kg	FRP	5.000/kg
Steel rebar global avg	2.289/kg	Epoxy	5.700/kg
Steel rebar UK 97% recycled EAF	0.835/kg	Rubber	2.660/kg
Stone	0.138/kg	Bearings	1.630/kg
Timber (sawn)	0.587/kg	Water supply	0.344/m^3
Portland cement, CEM I	0.860/kg	Diesel (100% mineral) *	3.314/l
Mineral aggregate	0.003/kg	Diesel (biofuel blend) *	3.156/l
Asphalt	0.380/kg	Electricity UK	0.233/kWh
PVC pipe	2.560/kg	Articulated diesel HGV	0.776/km

* Equipment consumption from datasheets (l/h); RT Crane 45T (18.2); Barge B < 20m (6.0), JX Piling Rig (7.0) Cat 325 1.5 CY backhoe (23.2), Generic 5HP diesel water pump (0.80, Compressor Kaeser Honda G360 (6.0), Cat D7 Dozer (34.0), Asphalt mixer 16HP (9.2)

3.2 Restoration Tasks

A three-span river-crossing bridge with shallow foundations is considered for this assessment (Fig. 2a). The fragility curves (Fig. 2b) and restoration models (Fig. 2c) were taken from previous research [4, 5], correspondingly, for four damage states (minor, moderate, extensive, severe). Nine scour depths ranging from 1.0 to 5.0 m with a step of 0.5 m were analysed. Only one pier foundation was scoured. These scenarios lead to a sequence of restoration tasks (R), for various damage states: minor (1, 11, 12, 14, 5), moderate (1, 11, 6, 12, 14, 16, 15, 5), extensive (1, 11, 6, 12, 14, 2, 16, 5, 15), and severe (1, 11, 6, 12, 14, 2, 5, 16, 15, 23). Below, the task ID is followed by the name, weighing factors for damage states (minor/moderate/extensive/severe), and the description of materials and processes.

- R1 Armouring countermeasures and flow-altering/cofferdam (0.70/0.80/0.90/1.00) pre-dredging, driving the support piles, bracing, 35 m diameter cofferdam with UBP 305 × 305 × 223 struts, sheet piles, and temporary works, fuel, transportation, and consumable materials.
- R2 Temporary support per pier (0.70/0.80/0.90/1.00) two temporary support frames incorporating UC 305 × 158 columns and UB 1016 × 305 × 494 beams, and associated platforms, consumables, installation and disassembly, transportation.
- R5 Repair cracks and spalling with epoxy and/or concrete (0.50/0.70/0.85/1.00) scaffolding, removal of 50 mm of concrete, new concrete, resurfacing, new parapets, drainage pipes, consumables, on-site activities, transportation, demolition waste.
- R6 Re-alignment and/or levelling of pier (0.50/0.70/0.85/1.00) assembly and disassembly of temporary frames, scaffolding, consumables, transportation.
- R11 Erosion protection measures (0.70/0.80/0.90/1.00) excavation, manufacturing and assembly of gabions, steel and stone materials, intervention measures cover both riverbanks, upstream, and downstream for 50 m, transportation.
- R12 Rip rap and/or gabions for filling of scour hole and scour protection (0.70/0.80/0.90/1.00) riverbed compaction, rip-rap placement and compaction, transportation of materials and some excavated soil within the site.
- R14 Ground improvement per foundation (0.70/0.80/0.90/1.00) excavation around the foundation, installation of a 2 m deep compacted gravel layer, associated materials and consumables, support system as for R2, transportation.
- R15 Installation of deep foundation system (1.00/1.00/1.00/1.00) 16 piles of 800 mm diameter and an RC pile cap of 3.5 × 5.5 × 1.5 m with a gross longitudinal rebar ratio of 4%, materials, on-site activities, transportation, temporary frames.
- R16 Extension of foundation footing (1.00/1.00/1.00/1.00) footing extension on all sides by 2 m over a depth of 1.5 m, some concrete removal, formwork, materials, transportation, demolition waste.
- R23 Demolish/replacement (part) of the bridge (1.00/1.00/1.00/1.00) a pier, and two decks are being replaced, thus R1, R18, 19, and R22 are considered.

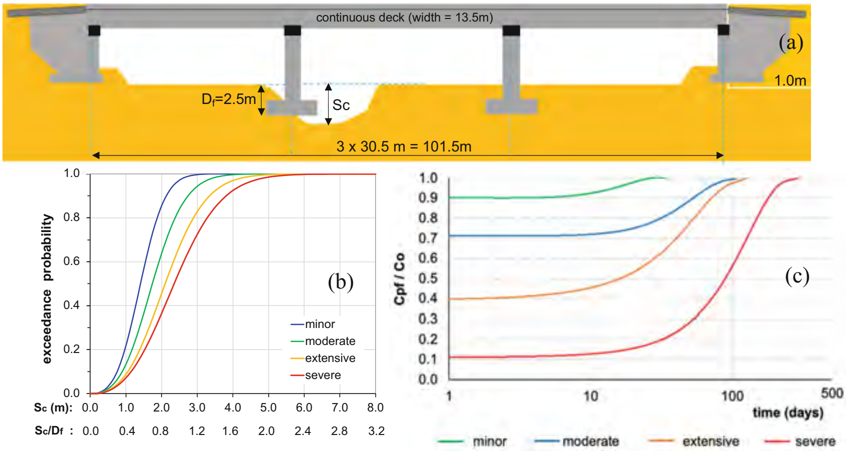

Fig. 2. (a) The reference bridge of the case study, (b) fragility curves of the bridge as a function of the scour depth (Sc) and the normalised Sc / D_f (D_f: foundation depth), (c) restoration curves of the bridge as a function of time (C_{pf}: post-flood capacity, C_o: original capacity) [2].

4 Results and Discussion

4.1 Environmental Impact

According to Table 2, tasks with more temporary works and fewer new materials (R1 and R2) have similar emissions from materials and equipment fuel consumption. Tasks with more new concrete and rebars have higher emissions from materials (R16). The literature shows that around 80% of the emissions are associated with materials extraction and production, which is similar to the average of the baseline analysis [9]. Both assessments assumed the same duration for all restoration tasks, regardless of the materials used. It is assumed that the use of low-carbon materials does not affect task duration and that these materials are available from the same manufacturers as conventional materials. Changes in task duration can impact on-site emissions, but materials and transportation remain constant. Longer construction tasks and associated materials can lead to 50% higher emissions due to higher fuel consumption (R1).

Figure 3a and Fig. 3b illustrate the weighted tCO2e per damage state and restoration task (R_i), using the weighting factors described in the previous section. Figure 3a corresponds to the conventional restoration strategies, whereas Fig. 3b refers to the low-carbon restoration approach. It is noted that for R23 the maximum values 1986 and 860 are given in the graphs, as these well exceed the max value of the tCO_2e axis. It is observed that conventional and low carbon strategies have similar emissions for R1, R11, R12, R6, R2, R14, and R5, with differences up to 15%. For R16, R15, and R23 significant differences were observed varying from 40% to 57%.

Table 2. Environmental impact assessment results.

Task	Conventional materials (tCO_2e)	On-site activities (diesel) (tCO_2e)	Transportation (diesel) (tCO_2e)	Total (tCO_2e)	Low carbon solution(1) (%)	Influence of duration(2) (%)
R1	16.9	63.6	0.1	80.6	−14.9	± 49.8
R2	2.7	4.9	0.1	7.7	−9.6	± 30.6
R5	18.3	1.1	1.2	20.6	−17.6	± 3.8
R6	3.4	0.7	0.1	4.2	−13.4	± 7.5
R11	645.5	29.0	3.5	678.0	−4.6	± 1.7
R12	21.7	2.5	0.1	24.3	−1.0	± 6.1
R14	29.0	5.0	0.3	34.3	−1.3	± 7.0
R15	235.0	113.9	0.4	349.2	−38.3	± 10.5
R16	346.5	16.2	0.2	362.9	−57.4	± 1.7
R23	1867.1	112.8	5.7	1985.6	−56.7	−3.3

(1) replacement of main construction materials and fuel with low-carbon alternatives;
(2) increase/decrease of carbon corresponding to the use of onsite equipment and machinery [2].

Close inspection of the emissions divided by materials, on-site activities, and transportation, indicate that materials can account for 21% to 99% of the emissions, with an average of 74% for all activities. On-site activities can represent 2% to 100% of the emissions, while transportation is up to 6%. Some restoration tasks have similar values to those found in the literature (i.e. construction activities contribute to 30% of the total, and transportation is around 4%). The environmental impact of traffic diversion due to structure closure can be significant in relation to the restoration of the asset [10].

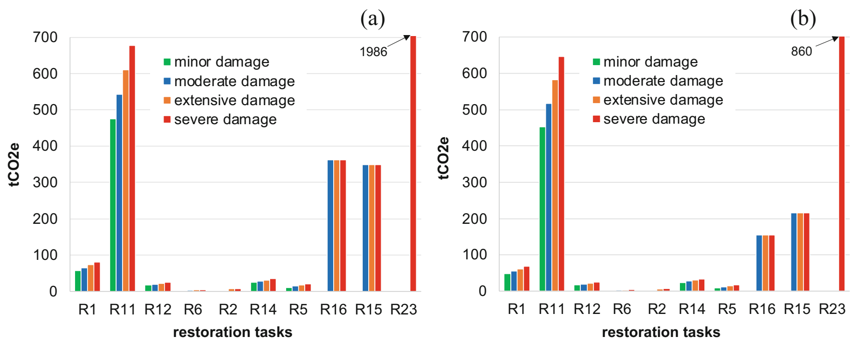

Fig. 3. (a) Weighted tCO2e per damage state and restoration tasks (R_i) for (a) conventional restoration and (b) low carbon restoration.

Normalised tCO_2e versus the resilience index R relationships for the nine scenarios examined, indicate that the highest emissions are for a scour depth of $S_c = 5.0$ m, whilst the lowest for $S_c = 1.0$ m. For the low-carbon case these are always smaller than for the conventional case, as expected. The differences in tCO2e are slightly smaller at lower hazard intensities and are higher by up to 60% for higher hazard intensities (e.g. $S_c = 5.0$ m). Regarding the sustainability index (S), this is 1.0 for low hazard intensity and low carbon solutions and increases with hazard intensity and use conventional materials.

Assuming various weighing cost factors (>1.0) for low-carbon materials, it is shown that the cost of the greener solution is up to 20% higher on average. However, the low carbon restoration strategy results in a 50–60% decrease in total tCO2e, encouraging the use of more sustainable solutions. For this case study a realistic hazard curve (peak flow versus return period) was adopted based on closed-form solutions available in the literature. Curves considering an increase in peak flow discharge due to climate change potential were also investigated [2]. Note that the results from this paper are specific for the case study and include expected uncertainty in LCA modelling due to assumptions outlined in Sect. 3.

4.2 Circularity Considerations

In asset restoration, the primary objectives revolve around minimizing the environmental impact caused by the interventions. Whilst this reductionist sustainability approach has its merits, using a circular approach in such interventions will enable quicker regeneration of the environment. In the built environment, circularity includes three main principles: (i) durability, referring to building and elemental service life planning, (ii) adaptability, the extension of the service life of the asset as a whole; and (iii) waste reduction and high-quality waste management, as well as future circular reuse of components and parts, or high-quality recycling of elements following deconstruction.

The effectiveness of implementation of circularity is typically assessed through indicators. In buildings, there are three sub-indicators for circularity: material, product, and system circularity [11]. Whilst circularity tools exist for buildings, there are limited assessment tools to ascertain the level of circularity in infrastructure [12]. These papers looked at design input, resource availability, adaptability, and reusability, highlighting the importance of circularity indicators in transport infrastructure projects.

As future directions, in the case of post-hazard interventions in asset restoration, the rehabilitation strategies could adopt circularity approaches. Specific indicators and decision trees based on circularity hierarchy levels can be developed for systematic decision-making. These could include the potential for reinstatement/rehabilitation, routes for harvesting components, and exploring upcycling/reuse in structures. Temporal-scale dependent life-cycle assessment would need to be carried out according to relevant asset functionality phases.

5 Conclusions

This paper described a framework for optimizing environmental sustainability, climate resilience, and cost in post-hazard transport asset recovery. The focus was on integrating the environmental impact assessment with resilience metrics. The conceptual framework and the environmental modelling assumptions were first provided. Carbon equivalent emissions were evaluated for various restoration tasks for a bridge affected by nine flood scenarios, considering conventional and low carbon solutions. After normalizing them into a sustainability index, these were combined into a global index with resilience and cost. Circularity considerations were also given.

The results show that restoration tasks with more temporary works and fewer new materials have relatively low emissions, in comparison with tasks that are materials intensive. Materials can account for 21% to 99% of the emissions. On-site activities can represent 2% to 100% of the emissions, while transportation is up to 6%. Low carbon solutions can provide up to 57% carbon reductions, at an increase in cost of about 20%. Longer construction tasks can lead to a 50% increase in emissions due to higher fuel consumption by construction equipment. Close inspection of the normalised emissions versus the resilience index for the nine scenarios indicated that the highest emissions are for the highest scour depth, whilst the lowest emissions for the lowest depth.

These results give an indication of the environmental impact of post-hazard interventions in transport asset recovery, and the suggested metrics can be adopted to prioritise asset recovery. The circularity indicators and hierarchy levels mentioned provide further insight into enabling more sustainable interventions that align with the wider planetary recovery drivers.

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Resilience Framework for Aged Bridges Subjected to Human-Induced Hazard - Case Study in Ukraine

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Abstract. Bridge structures are key components of transport networks, enabling connections between important centres and regions of countries. Their operability and functionality loss due to long-term deterioration or extreme hazards could cause crucial social and economic impacts. Assessment of bridge resilience against these hazards is needed to predict functionality, optimal management, sustainable development, and decision-making in maintenance and post-conflict restoration measures. Nevertheless, no studies exist to date to optimize resilience metrics for aged bridges subjected to human-induced stressors, considering indirect losses due to disruption of the transport network. This is a capability gap that gave the motivation for this research paper. The study covers functionality-related resilience metrics of damaged bridges, associated with direct losses in terms of repair cost, and socio-economic metrics due to the inoperability of the logistic route. The application of a framework for resilience assessment was illustrated with an example of the case study of the post-conflict restoration of Ukrainian aged bridge structures, which experienced extensive war-induced destruction. This research presents a novel application of resilience framework for assets, subjected to war-induced stressors, considering both direct and indirect losses, and introduces cost and safety-based resilience indexes.

Keywords: Resilience · Bridges · Damages · Deterioration · Post-conflict Recovery · Ukraine

1 Introduction

Bridges play a key role in the performance of infrastructural systems, enabling communication between different regions across any country. In addition to general ageing and deterioration, these structures are often subjected to different natural disasters (earthquakes, floods, tsunamis) and human-induced hazards (e.g. artillery fire during the conflict), which is often the reason for their inappropriate state and limited functionality. The probable bridge failure leads to significant social and economic consequences due to the worsening of logistic routes and the inability of effective post-hazard recovery, which is a common problem in many countries nowadays [1, 2].

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In general, resilience is the system's ability to withstand and recover from a catastrophic event. Its assessment, as defined in [3–5] encompasses dimensions in technical, organizational, social, and economic sectors. System resilience hinges on the following properties: robustness, redundancy, resourcefulness, and rapidity. Robustness signifies the system's capacity to maintain functionality under varying hazard intensities. Redundancy assesses the availability to replace system components if functionality decreases. Resourcefulness refers to the system's ability to quickly respond to external threats and utilize available resources. Rapidity measures how quickly the system regains functionality after a hazard, minimizing downtime [3, 4]. Integrating these parameters resilience metrics are obtained, aiding efficient decision-making for post-disaster recovery.

The resilience assessment, thus, covers three targeted outcomes: low probability of failure, limited probability of critical consequences, and rapid recovery. Recovery planning, prevention of further damage propagation, and optimization of resources' use are vital operations for incentivizing infrastructure recovery and post-conflict rehabilitation in war-torn countries. Resilience quantification for restoring vital bridges should account for both structural and transportation capacity. This involves functionality-based and socio-economic metrics, addressing direct and indirect losses due to disrupted transportation routes. Alternative scenarios for enhancing resilience due to the reduction of indirect losses can be considered with the use of benefit-cost models [6]. Functionality-based resilience (robustness, resourcefulness, redundancy, rapidity), is normally evaluated as a function of the area under the functionality curve $Q(t)$ within the specific timespan. For bridges, being the backbone of the recovery process, socio-economic metrics should additionally be considered. Thus, recent studies [2–4] refer to the cost-based resilience index, which takes into account both direct and indirect losses due to traffic detours and delays.

Failure or damage of bridges has considerable socio-economic consequences for the sustainability of overall transport infrastructure, e.g. environmental footprint, life-quality impact, etc. This highlights the necessity of sustainable restoration strategies placing particular focus on selecting alternative materials, reducing material consumption, and incorporating local or recycled materials. Energy consumption and environmental impact are also critical sustainability metrics, as the recovery of hazard-damaged structures entails additional energy expenditure and increased emissions during restoration [7]. Implementing ongoing hazard-resilient structural designs, considering local conditions, would provide the synergic effect of the potential reduction in social, environmental, and economic impacts from hazard exposure, which is especially relevant for post-conflict recovery in war-torn regions [7]. However, rapid budget assignment and additional initial investment of resources associated with enhanced hazard protection design and sustainable restoration could be challenging in case of post-conflict recovery of the entire region in limited-cost conditions. [7]. Considering all the stated above, the efficient and optimal recovery process of bridges, subjected to multi-hazard environments (e.g. war-induces explosions and general deterioration) requires preliminary evaluation of direct and indirect losses, sustainability and resilience metrics for thorough planning, prioritization and decision-making. Although, previous studies introduced approaches for the assessment of resilience, only a few of them consider indirect losses, associated with the inoperability of transport infrastructure and there is a very limited amount of research on resilience to human-induced stressors (e.g. war, and terrorist attacks). Most existing studies were focused on natural hazards, while the failure of a bridge during the hostilities is a complex issue, requiring consideration of proximity factors and increased downtime due to limited access to assets, which is a novel aspect, covered in this research. In the face of the enhanced risk of terrorist attacks worldwide, a reliable approach for strategic planning and recovery prioritization reaches topicality for any country. This paper fills this gap of knowledge, introducing a resilience framework, which takes into account indirect losses due to inoperability of a logistic route with the use of cost- and safety-based indexes. The proposed framework is of significant practical relevance for regions facing similar hostilities or having a high risk for terrorist attacks, e.g. areas with political and socio-economic instability, ethnic or religious tensions, or active conflict zones. In this study the application of a framework is illustrated with an example of the post-conflict restoration of Ukrainian aged bridges, demonstrating real-world applicability. Ukraine, having 55% of the arable land area is one of the world's top agricultural producers, thus disruption of logistic routes will lead to global negative consequences on both regional and international scales, which makes bridges of Ukraine an effective case study for illustration of the resilience framework.

2 Resilience Framework for Combined Ageing and Human-Induced Hazards

The resilience assessment framework, proposed in international literature [1, 2] was adopted and modified for application for post-conflict recovery (see Fig. 1).

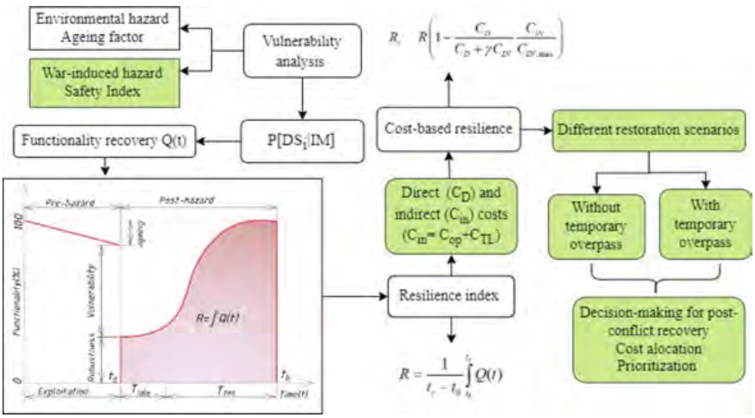


Fig. 1. The flowchart for resilience assessment (novel aspects highlighted with green).

In particular, the unique aspects of human-induced hazards as the proximity to more affected zones and increased downtime were introduced. to multi-hazard environment. Assessment of vulnerability to multi-hazard environment integrates two negative factors: (1) general deterioration due to long-term exploitation and (2) war-induced damages, caused by explosions/ artillery fire. Equation (1) describes the fragility (Frag) of structure as the probability (P) of being in one of the damage states (DS_i, i = [0…4]) for the particular hazard intensity measure of explosion (IM). In this work damage states are defined as intact (DS0), slight damages (DS1), moderate damages (DS2), considerable damages (DS3) and total failure of the bridge (DS4) [2].

$$Frag = P[ds > DS_i|IM], \; i = [0...4] \tag{1}$$

The resilience curve for bridges subjected to explosion can be described by Eq. (2). It is based on restoration functions [2], which indicate the rapidity of functional recovery of the structure from various DSs, considering the probability of its occurrence.

$$Q(t) = \sum_{i=0}^{4} Q[DS_i|t]P[DS_i|IM], \tag{2}$$

where the function $Q[DS_i|t]$ describes the level of functionality of the bridge at t time of restoration from each DS.

Next, the resilience index is determined as the area under the Q(t) normalized by a target time or maximum restoration time (t_r) [2], which is calculated with Eq. (3):

$$R = \frac{1}{t_r - t_0} \int_{t_0}^{t_r} Q(t), \tag{3}$$

where t_0 defines the time point when the explosion occurred and t is a variable, which includes both, the idle time and restoration time.

Resilience index in Eq. (3) is associated with functionality-related resilience metrics due to direct losses caused by damage/ failure of the bridge. However, it is important to consider bridges as important parts of transport infrastructure, the failure of which leads to considerable indirect losses due to limited or impossible operability of communication routes. Thus, socio-economic metrics of resilience can be considered with the use of cost-based resilience index R_c [2, 3]:

$$R_c = R\left(1 - \frac{C_D}{C_D + \gamma C_{IN}} \frac{C_{IN}}{C_{IN,\max}}\right), \tag{4}$$

where C_D defines the direct costs for repair of the bridge, considering the probabilities of damage in different damage states DS_i:

$$C_D = C \cdot W \cdot L \sum_{i=0}^{4} (P[ds = DS_i|IM] \cdot DR_i), \tag{5}$$

where C indicates the repair cost for 1 m^2 of a bridge of similar type, W and L are its width and length, and DR_i is a ratio of repair cost according to the level of damage. The probability of occurrence of particular DS, if a hazard has intensity IM ($P[ds = DS_i|IM]$) is then:

$$P[DS_i|IM] = \begin{cases} P[ds > DS_{i+1}|IM] - P[ds > DS_i|IM] & \text{if i = 1...3} \\ P[ds > DS_i|IM] & \text{if i = 4} \end{cases} \tag{6}$$

In addition to direct costs, the indirect losses due to the necessity of detour include the operating costs of vehicles on a detour (C_{OP}) and the costs due to vehicle time loss (C_{TL}) [2, 8] (see Eqs. (7), (8)).

$$C_{OP} = \sum_{i=1}^{4} \left\{ P[ds = DS_i|IM] \left(T_{idl,i} + \frac{T_{res,i}}{2} \right) \left[C_{OP,car} \left(1 - \frac{TR_D}{100} \right) + C_{OP,truck} \frac{TR_D}{100} \right] D_l ADT \right\}, \quad (7)$$

$$\cdot C_{TL} = \sum_{i=1}^{4} \left\{ \begin{array}{l} P[ds = DS_i|IM] \left(T_{idl,i} + \frac{T_{res,i}}{2} \right) \left[\begin{array}{l} C_{AW} O_{car} \left(1 - \frac{TR_D}{100} \right) \\ + \left(C_{ATC} O_{truck} + C_{goods} \right) \frac{TR_D}{100} \end{array} \right] \frac{D_l}{S} ADT \\ + ADE \left(\frac{1}{S_D} - \frac{1}{S_0} \right) \end{array} \right\}, \quad (8)$$

where $T_{idl,i}$, $T_{res,i}$ are idle and restoration time of a bridge from particular DS; $C_{OP,car}$, $C_{OP,truck}$ indicate the average cost of cars and trucks operation; D_l denotes additional length due to detour; ADT and ADE are average daily traffic on the detour and remaining daily traffic on the bridge after the damage occurred; TR_D is a percent of trucks in the daily traffic; C_{AW}, C_{ATC} and C_{goods} define the average wage, total compensation and the cost to transport goods in cargo (per hour); O_{car} and O_{truck} are daily vehicle occupancy for cars and trucks, respectively; S, S_D and S_0 are the average velocity on the detour, on the damaged and intact bridge, respectively [2].

3 Case Study of Post-conflict Recovery in Ukraine

3.1 Portfolio of Bridges

Russian invasion in Ukraine has caused significant damages to Ukrainian infrastructural assets, especially bridges, and it can be expected, that bridges will continue playing a key role until the end of the war, whenever that is, being fought over, defended, and attacked [8–10]. As the "key terrain" in military circumstances, these structures with high probability will be subjected to significant damages or even total failure, due to explosions, artillery fire, shelling, or targeted destruction for strategic purposes.

In addition, it has to be considered, that even before the beginning of the war in Ukraine, their technical state and capability to meet the requirements for carrying capacity and dimensions of today's roadway were of considerable doubt. According to recent reports from regional authorities [11, 12], about 81% of bridges were built before 1981 and most of the biggest bridges have the age of over 60 years. Thus, it is obvious, that the post-conflict recovery in Ukraine will include the necessary restoration of bridge structures, which requires optimal planning and strategic approach.

For this purpose, the resilience of the 18 biggest bridges in Ukraine was assessed, according to the methodology, described in the previous section. The following Table 1 gives a summary of information about the analysed assets.

3.2 Vulnerability Analysis

In order to assess the vulnerability of bridges, they were ranged, according to relative distance from the front line (autumn, 2023). Thus, assets were grouped according to the probability of war-induced damage and corresponding safety indexes (SI) were

Table 1. Portfolio of 18 biggest bridges in Ukraine.

No	Name	Coordinates	Year of constr. (repair)	L/W (m)	Type*
1	Petrivsky Bridge, Kyiv	50.4837°, 30.548°	1945 (2005)	1430/5	1
2	Darnytsky Bridge I, Kyiv	50.416°, 30.586°	1949	954/15	2
3	Kryukiv Bridge, Kremenchuk	49.053°, 33.424°	1949	1700/8	2
4	Marefa-Kherson Bridge, Dnipro	48.467°, 35.083°	1951	1627/5	3
5	Preobradgensky Bridge I, Zaporizha	47.846°, 35.086°	1952	560/15	3
6	Preobradgensky Bridge II, Zaporizha	47.821°, 35.075°	1952	228/15	3
7	Paton Bridge, Kyiv	50.427°, 30.582°	1953	1543/21	4
8	Antoniv Bridge I, Kherson	46.676°, 32.796°	1954	514/6.7	1
9	Amur Bridge, Dnipro	48.488°, 35.028°	1955 (2002)	1395/15.5	1
10	Southern Bug Bridge, Mykolaiv	46.987°, 31.964°	1964 (2004)	750.7.15.7	5
11	Metro Bridge, Kyiv	50.443°, 30.565°	1965	682.6/28	3
12	Central Bridge, Dnipro	48.477°, 35.057°	1966 (2019)	1478/21	5
13	Northern Bridge, Kyiv	50.491°, 30.536°	1976	816/31.4	6
14	Kaidatsky Bridge, Dnipro	48.501°, 34.968°	1982 (2019)	1732/26	5
15	Antoniv Bridge II, Kherson	46.670°, 32.720°	1985	1366/25	5
16	Southern Bridge, Kyiv	50.395°, 30.589°	1990	1256/41	6
17	Southern Bridge, Dnipro	48.410°, 35.097°	2000	1248/22	5
18	Darnytsky Bridge II, Kyiv	50.416°, 30.586°	2010	1066.2/43.8	2

* Note: 1-truss; 2-combined structure (frame + reinforced concrete (RC) arch); 3-RC arch; 4-steel welded; 5-RC beam; 6-cable stayed

assigned: for bridges in Kyiv (High SI zone)−0.9…1, in Kremenchuk, Dnipro (Medium SI zone)−0.3–0.6, in Zaporizha, Kherson, Mykolaiv (Low SI zone),−0.01–0.2 (proximity based SI). Here as reference served Kherson bridges, which were destroyed [13]. Thus, based on the described above, values of $P[ds > DS_i|IM]$ and $P[DS_i|IM]$ were chosen for each asset (see Table 2). Such a novel approach can be alternatively used for other applications, e.g. terrorist attacks.

To take into account the deterioration of aged bridges, the ageing factor S_{age} was introduced for those, built before 2000 (similarly to [2]), reflecting the reduction of load-bearing capacity by 2.5% for DS1, 5% for DS2, 7.5% for DS3 and 10% for DS4. Although certain restoration measures were made for the most critical assets (see Table 1), they mostly slowed down the process of destruction, rather than fully restoring the capacity of assets. Such minor repair works were considered as a reduction of exploitation time by one decade.

Table 2. Probability of exceedance of DS_i occurrence, considering proximity-based SI

No	$P[ds > DS_i\|IM]$				$P[DS_i\|IM]$			
	DS0	DS1	DS2	DS3	DS4	DS0	DS1	DS2	DS3
1	1	0.25	0.2	0.15	0.75	0.05	0.05	0.05	0.1
2	1	0.25	0.2	0.15	0.75	0.05	0.05	0.05	0.1
3	1	0.5	0.45	0.4	0.5	0.05	0.05	0.05	0.35
4	1	0.75	0.7	0.65	0.25	0.05	0.05	0.05	0.6
5	1	0.85	0.8	0.75	0.15	0.05	0.05	0.05	0.7
6	1	0.85	0.8	0.75	0.15	0.05	0.05	0.05	0.7
7	1	0.25	0.2	0.15	0.75	0.05	0.05	0.05	0.1
8	1	0.95	0.9	0.85	0.05	0.05	0.05	0.05	0.8
9	1	0.75	0.7	0.65	0.25	0.05	0.05	0.05	0.6
10	1	0.85	0.8	0.75	0.15	0.05	0.05	0.05	0.7
11	1	0.25	0.2	0.15	0.75	0.05	0.05	0.05	0.1
12	1	0.75	0.7	0.65	0.25	0.05	0.05	0.05	0.6
13	1	0.25	0.2	0.15	0.75	0.05	0.05	0.05	0.1
14	1	0.75	0.7	0.65	0.25	0.05	0.05	0.05	0.6
15	1	1	0.95	0.9	0	0.05	0.05	0.05	0.85
16	1	0.25	0.2	0.15	0.75	0.05	0.05	0.05	0.1
17	1	0.75	0.7	0.65	0.25	0.05	0.05	0.05	0.6
18	1	0.25	0.2	0.15	0.75	0.05	0.05	0.05	0.1

3.3 Resilience Analysis

The time required for restoration of each bridge in particular DS was assumed, according to previous works [2, 14] as 90 d/1000 m^2 for full restoration (DS4). For bridges with partial damages, this time duration was reduced by 10% for DS3, by 25% for DS2 and by 75% for DS1, based on engineering judgment.

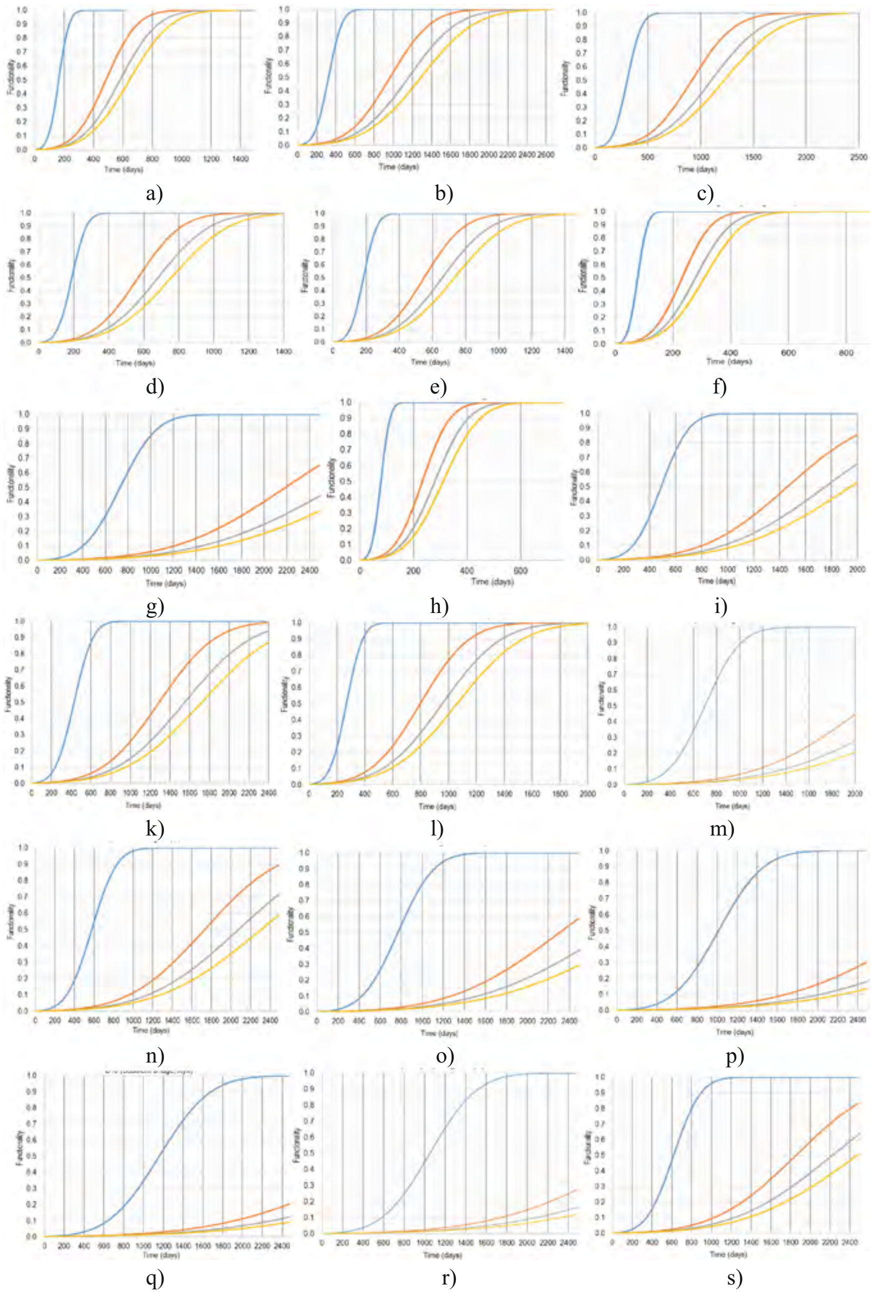
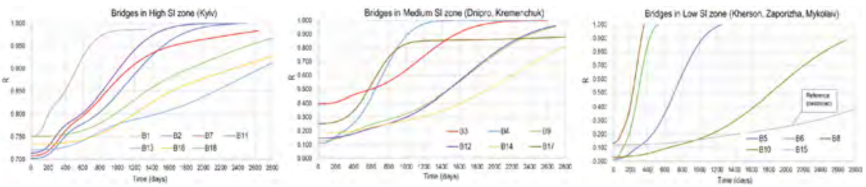


Fig. 2. Restoration curves for bridges B1-B18 (a-s):—-DS1,—-DS2,—-DS3,—-DS4.

Similarly, values for the T_{idl} were taken according to the assumption in [2] as 15 days for DS1, 30, - for DS2, 45, – for DS3, 60, -for DS4 (as higher levels of damage would require more time for preparation of restoration project and allocation of costs for it).

The duration of idle time was further adjusted according to the safety factor to consider the inability to begin restoration works on the territories, close to the front line. As the duration of restoration works is a stochastic value with high uncertainty, the MC simulation was performed to introduce probabilistic model, using a cumulative normal distribution with a standard deviation of 0.35 × mean. Thus, restoration curves were plotted for each bridge in different DSs (see Fig. 2), according to Eq. (2). Similarly, from Eq. (3), resilience curves were obtained and grouped by safety indexes (see Fig. 3).



g) h) i)

Fig. 3. Resilience values for bridges in different SI zones: a) high, b) medium, c) low.

For all the examined bridges the general rapidity of functionality restoration decreases with the increase of damage level (from DS1 to DS4), while the greatest difference can be noted between DS1 and DS2. It should be noted, that as for estimation of the resilience values was based on the MC approach, the probability density function of restoration time was considered, rather than the mean value. Although this assumption is case-specific and provides restoration time much higher, than those in the deterministic approach [2], it more reliably represents uncertainty conditions. Resilience curves in Fig. 3 illustrate functions of achievement of different R values for particular restoration time and ideally should asymptotically reach the full functionality equal to 1. However, although the final restoration time was limited by the same value, for some of the assets the functionality was not 100% restored. As can be seen, resilience values are strongly dependent on the probability of occurrences of DSs, thus the bridges could be grouped according to SI zones. For bridges with the lowest probability of significant damages (High SI), the R values follow a similar trend, while the most rapid resilience increase is for B1 and the slowest, - for B13, which is mostly determined by their area. Similarly, within the bridges in the Medium SI zone, the lowest R values were determined for the bridge with the biggest area (B14) and the sharpest R increase, -for the smallest (B4). Resilience curves for other bridges were equally influenced by the age of assets and the dimensions. In the third group of bridges it was found, that although the starting R value was different for B6 and B8 (different probability of significant damages due to location), their resilience values increased with the higher intensity, compared to B5 and B10 due to smaller dimensions. The lowest resilience was identified for B15, determined equally by the highest probability of failure and big area.

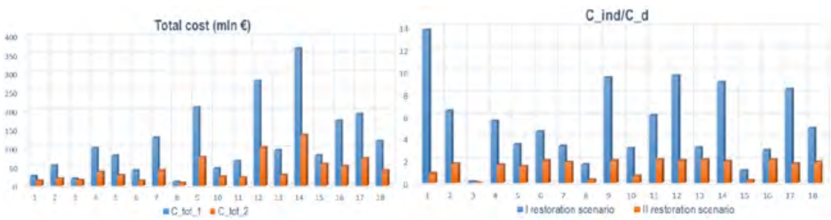
3.4 Cost-Based Resilience

Functionality-based metrics, introduced in the previous section are associated with direct losses and are unchanged during the time. However, disruption of the functionality of bridges results in indirect losses due to the worsening of transport network, which are time-dependent and have to be additionally considered in this case study. Thus, direct and indirect losses were calculated, according to Eq. (5), (7), (8).

Direct costs for restoration of bridge were calculated, considering costs for each bridge type in Ukraine (see Table 1): 1st type-1500 €/m^2, 2nd and 3d-3000 €/m^2, 4th and 6th - 5500 €/m^2, 5th -1400 €/m^2. DR values were assumed as 0, 0.03, 0.08, 0.25 and 0.75 for DS1-DS4, respectively [2].

For calculation of indirect losses $C_{op,car}$ and $C_{op,truck}$ were assumed equal to 0.2 and 0.3 €/km, $TR_D = 20\%$, C_{AW}, C_{ATC} and C_{goods} were equal to 1 €/h, $S_D = 50$ km/h, $S_0 = 90$ km/h, $S = 40$ km/h, $O_{car} = O_{truck} = 2$.

High indirect losses due to timely restoration works initiated the introduction of an alternative restoration scenario with a temporary overpass, which is a novel approach in this study. This enabled the partial operation of transport routes by cars. The cost of the overpass as 4000 €/m was added to direct costs for Scenario 2. Calculated direct and indirect costs are presented in Fig. 4.



a) b)

Fig. 4. Assumed restoration costs (a) and ratio between indirect and direct costs (b) for 2 restoration scenarios.

Cost-based resilience for each bridge was calculated according to Eq. (4) (see Table 3), considering different levels of socio-economic impact of a bridge failure ($\gamma = 0.05\ldots0.15$).

The socio-economic impact of indirect losses is evidently represented by C_{ind}/C_D which shows the consequences of indirect losses for different assets and could be considered as objective measures to facilitate decision-making in recovery prioritisation. Thus, the highest impact of indirect losses was estimated for bridges B1, B9, B12, and B17. However, the introduction of a temporary overpass will enable to partly eliminate these consequences. Although the total costs are lower for the second restoration scenario (see Fig. 4a), it is associated with the fastened allocation of considerable costs required for the construction of temporary overpasses. Also, according to obtained results, the level of socio-economic impact of a bridge failure (γ) has a higher impact on the resilience index for the II restoration scenario, especially for bridges with higher area (e.g. B14, B17, B12, B9), due to longer time of bridge inoperability.

Table 3. Cost-based resilience indexes and direct and indirect losses for 18 bridges.

		I Scenario				II Scenario			
	R	$\frac{C_{ind}}{C_D}$	C_{tot} (mln €)	Rc (γ = 0.05)	R_c (γ = 0.15)	$\frac{C_{ind}}{C_D}$	C_{tot} (mln €)	Rc (γ = 0.05)	R_c (γ = 0.15)
1	0.985	13.71	26.49	0.988	0.993	0.90	14.25	0.929	0.934
2	0.999	6.49	54.98	0.983	0.992	1.74	20.48	0.867	0.886
3	0.995	0.14	19.04	0.998	0.998	0.04	15.78	0.993	0.993
4	0.997	5.56	101.29	0.979	0.991	1.65	37.64	0.775	0.823
5	0.985	3.45	81.37	0.981	0.992	1.51	28.59	0.829	0.858
6	0.993	4.60	41.72	0.986	0.993	2.02	13.98	0.902	0.913
7	0.988	3.31	128.82	0.978	0.991	1.88	41.31	0.746	0.806
8	0.999	1.68	11.33	0.995	0.996	0.31	8.22	0.979	0.979
9	0.941	9.45	210.11	0.975	0.991	2.02	77.50	0.573	0.717
10	0.859	3.11	47.19	0.985	0.993	0.64	25.04	0.899	0.910
11	1.000	6.07	66.83	0.982	0.992	2.10	23.11	0.843	0.868
12	0.930	9.64	280.54	0.974	0.991	2.03	103.48	0.474	0.677
13	0.847	3.18	95.22	0.980	0.992	2.08	29.23	0.806	0.843
14	0.811	9.03	367.28	0.973	0.990	1.95	136.33	0.375	0.643
15	0.386	1.11	81.89	0.984	0.992	0.25	58.77	0.879	0.894
16	0.928	2.95	173.99	0.977	0.991	2.08	52.48	0.682	0.770
17	0.880	8.44	192.29	0.975	0.991	1.75	73.71	0.604	0.731
18	0.967	4.92	120.25	0.978	0.991	1.89	41.68	0.744	0.804

4 Conclusions

The study presents a novel approach for the assessment of cost-based resilience of aged bridge structures, subjected to human-induced hazards (explosions, shelling, terrorist attacks in conflict areas). The framework was demonstrated with the case study of the 18 biggest bridges in Ukraine, which are the most crucial assets for transportation network functionality. Vulnerability and restoration analysis have shown that the most sensitive to distortion of operability are the bridges with the biggest restoration area due to the longer time, required for restoration and longer loss of functionality of transport route. Thus, indirect losses are the highest for the biggest bridges and assets with longer detour lengths, representing the socio-economic impact of indirect losses. Considering the increase of resilience during the restoration works was noted the strong dependency of the rapidity of functionality restoration on the probability of significant damages and the location of the bridge (the closeness to the conflict areas). Two restoration scenarios were considered associated with different levels of initial funding placement and fundraising rapidity, providing different ratios of indirect and direct losses and speed of functionality restoration. Resilience and sustainability metrics, discussed in the research provide a reliable framework for efficient and sustainable asset management, resource allocation and decision-making during post-conflict recovery.

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A Study on Traffic Awareness at Jordanian Universities: A Case Study of the German Jordanian University

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Abstract. Traffic safety, particularly among young adults, is a critical public health concern that necessitates a deeper understanding of the factors influencing driving behaviors and compliance with traffic regulations. This study, conducted at the German Jordanian University in Amman, Jordan, aimed to elucidate these factors by evaluating the traffic awareness and behaviors of a diverse group comprising students, academic staff, and other university employees. Employing a survey methodology, the research engaged over 500 individuals, yielding 300 responses. This survey revealed notable trends, for example, a significant portion of drivers exhibited non-compliance with speed limits and seatbelt usage, coupled with prevalent mobile phone usage while driving. A concerning observation was that the majority of respondents who had experienced one or two accidents fell within the 18–19 age range. The study also highlighted the perception of social media as the most effective medium for traffic awareness campaigns, in contrast to television, which was deemed the least effective. These findings underscore a pressing need for comprehensive traffic safety education, especially among younger drivers. The results advocate for the integration of Traffic Awareness as a mandatory module within university curricula, ensuring a structured and consistent approach to instilling the importance of traffic safety measures. Such an initiative could significantly contribute to reducing traffic-related incidents and fostering a culture of responsible driving within the university community.

Keywords: Traffic Awareness · Traffic Regulations · Traffic Safety Measures · Traffic Safety Curriculum Integration

1 Introduction

The expanding growth of educational institutions in Jordan paralleled with increased vehicle ownership and usage, has heightened the importance of studying traffic awareness in these microcosms of society. The German Jordanian University, located on the outskirts of Amman, presents a unique setting to explore these dynamics. It serves as a microcosm that encapsulates the complexities of Jordanian traffic, including issues

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related to student and faculty commuting, campus traffic management, and the interplay between university policies and national traffic regulations. This paper presents an in-depth study on traffic awareness in Jordan, focusing on a case study of the German Jordanian University (GJU), a prominent educational institution known for its blend of Jordanian and German academic cultures. This study aims to provide a nuanced understanding of traffic behaviors, perceptions, and safety measures within and around the university, reflecting broader trends and challenges in Jordanian urban traffic management. This case study is particularly relevant as it examines traffic awareness in a setting where young adults, a demographic crucial to the future of Jordan's road safety, are predominant. It explores how traffic awareness and behaviors are shaped by a combination of educational influences, cultural backgrounds, and the physical infrastructure of the university. The study seeks to answer critical questions: How does the university environment influence traffic awareness and behaviors? What role do educational programs and campus policies play in shaping students' and staff's attitudes toward road safety?

The outcomes of this study are anticipated to offer valuable insights for policymakers, educators, and urban planners. By understanding the specificities of traffic awareness in a university setting, more targeted and effective strategies can be developed to enhance road safety, not just within the confines of educational institutions but across the broader spectrum of Jordanian urban and suburban areas. As Jordan strides towards a future marked by urban development and technological advancement, fostering a culture of traffic awareness becomes paramount in safeguarding the well-being of its citizens, and this study contributes significantly to this critical mission.

2 Background

This literature review synthesizes key findings from existing research to provide a contextual foundation for understanding traffic awareness in Jordan.

2.1 Traffic Safety and Road Accidents in Jordan

Several studies have highlighted the growing concern for road safety in Jordan. Al-Khateeb, Ghazi (2010) emphasized the high prevalence of road traffic injuries in the Middle East, with Jordan experiencing a significant number of these incidents, often attributed to risky driving behaviors and inadequate road safety measures [1]. Similarly, several studies indicated that One-fifth of observed drivers are speeding, and One-fourth of observed drivers change lanes [3, 4]. The study recommends Improving the capacity of driving instructors through certification and follow-up and increasing practical and theoretical training hours for drivers.

2.2 Youth and Traffic Behavior

Focusing on the youth demographic, prevalent in university settings, research by a group of researchers examined the effect of teenage driving on mortality and risky behaviors in the United States [2]. The study indicates that teenage drivers are 6–9 times more likely to die per additional mile driven than adult drivers. This demographic's attitudes and behaviors are particularly relevant to the GJU context.

2.3 Impact of Educational Institutions on Traffic Awareness

Educational institutions can promote traffic awareness among students by creating educational programs and campaigns. Studies show that training on traffic rules and road safety improves awareness among students. Safety campaigns on campus significantly improve students' adherence to traffic rules. Integrating traffic education into university curricula is recommended to foster a culture of safety among young adults.

2.4 Urban Transportation and Campus Planning

The link between urban transportation and campus planning also forms a critical aspect of traffic awareness. Several studies highlighted the importance of integrating transportation planning with campus development, suggesting that well-designed campus environments can positively influence commuting behaviors and traffic safety [5, 6].

2.5 Gaps in Literature and Research Objective

While the existing literature provides comprehensive insights into various aspects of traffic awareness in Jordan, there remains a gap in research specifically focused on the traffic dynamics within university settings like GJU. Furthermore, the interplay between educational influence and cultural factors in shaping traffic behavior in such environments is an area that requires deeper exploration.

The review of existing literature indicates a critical need for targeted research in the context of academic institutions like GJU to develop effective traffic awareness and safety strategies. This study aims to address these gaps by focusing on the unique setting of GJU, offering insights that could inform broader traffic safety initiatives in Jordan.

3 Methodology

To achieve the research objectives, a structured survey was conducted, targeting specific groups. The survey, divided into several sections, was designed for comprehensive data collection, as shown in Table 1. The first section gathered demographic information, including age, marital status, and education level. The second section focused on respondents' driving behaviors to understand their daily driving experiences and habits. The final section assessed participants' views on traffic awareness and accident occurrences, providing insights into their perceptions. The survey, executed via Google Survey tool for broad access, was distributed to 500 individuals, with 300 responses received, resulting in an impressive 60% response rate, indicating high engagement in the targeted group.

Table 1. Survey Questions.

Question	Options				
1- Age?	18-25	26-33	34-41	41+	
2- Marital status?	Single			Married	
3- Do you own a vehicle?	Yes		No		
4- Age driving license was obtained?	18	19	20		20+
5- Education (highest degree completed/current)?	PhD	Master	Bachelors	Secondary or Higher	Less than Secondary
6- Current position?	Freelance	Private Sector	Public Sector	Student	
7-What is your total household income?	Less than 500	500-1000	1500-2000	2000+	
8- Do you wear a seatbelt while driving?	Always	Sometimes	Rarely		
9-Do you use a child's car seat?	Yes		No		
10- Where do you seat children under the age of 5?	In the back seat	In the passenger seat	On the driver's lap		
11-Do you obey the traffic lights?	Always	Sometimes	Rarely		
12- Do you drink cold or hot drinks while driving?	Always	Sometimes	Rarely		
13- Do you eat while driving?	Always	Sometimes	Rarely		
14- Do you continue to drive despite feeling fatigued or exhausted?	Yes		No		
15- Do you exceed the speed limit?	Always	Sometimes	Rarely		
16- Do you use your phone while driving?	Always	Sometimes	Rarely		
17- Do you use headphones while driving?	Always	Sometimes	Rarely		
18- Do you sit properly while driving?	Always	Sometimes	Rarely		
19- Do you litter while driving?	Always	Sometimes	Rarely		
20- How long does it take you to reach you work/school destination?	Less than 15 min.	15-30 min.	30-45 min.		45+ min
21- What type of car insurance do you have?	Comprehensive	Third Party Liability.	Not insured		
22- How often do you take your car or	Regu-	Occa-	Rarely		

(*continued*)

Table 1. (*continued*)

maintenance?	larly	sionally				
23- How many times have you been in a car accident?	0	1 or 2	3 or more			
24- If so, age of first accident:	Fill the blank					
25- In your opinion, what are the 5 most common reasons behind car accidents in your area?	Speeding	Drifting	Distractions	Blind Spots	Drivers Health Condition	Weather Conditions
26- In your opinion, what age group is more prone to car accidents?	Less than 16.	16-20.	21-30.	31-40.	40-50	50 +
27- In your opinion, when do most accidents occur?	In the Morning	At Noon	In the Afternoon	At Night	After Midnight	
28- In your opinion, what is the most common reason behind teenage fatal car accidents?	Intoxicated Drivers.	Texting/ Using Phones	Speeding/ Drifting Other			
29- In your opinion, rank the following means of traffic awareness from most important to least*	Television Programs	Radio Programs	Awareness Campaigns	Social Media		
30- In your opinion, does wearing a seatbelt reduce car accident harms?	Yes	No Sometimes	Always			
31- In your opinion, does using a phone while driving increase the risks of car accidents?	Always	Sometimes	Rarely			
32- Do you support introducing traffic awareness as an obligatory academic requirement in schools / universities?	Yes		No			
33- How do you estimate the rate of traffic accidents in your area?	1	2	3	4	5	

3.1 Descriptive Analysis

In this study, the methodological approach was structured into three distinct yet interconnected segments, each designed to provide a holistic understanding of traffic awareness among the target demographic. The methodology comprised demographic analysis, behavioral assessment, and opinion evaluation, thereby offering a comprehensive view of the variables influencing traffic safety and awareness.

Descriptive Analysis of Survey Responses

The survey was constructed to primarily target young drivers at the German Jordanian University. However, it also garnered participation from a broader spectrum including instructors, workers, and graduates. Figure 1 exhibits a range of visual representations pertaining to the survey questions featured in the study.

Fig. 1. Visual representations pertaining to some of the survey questions featured in the study.

Based on the survey response, the following is summarized:

1. Age Demographics: Predominantly young, with 73% aged 18–25.
2. Marital Status: 80% single, reflecting the youthful demographic.
3. Educational Level: 68.3% hold a bachelor's degree; smaller percentages have higher or secondary education.
4. Driving License Acquisition: 72.7% got their license at 18; 13% over 20.
5. Vehicle Ownership and Insurance: 74% own a vehicle; diverse insurance types noted.

6. Vehicle Maintenance: 45% regularly maintain their vehicles.
7. Accident Involvement: 47% involved in one or two accidents.
8. First Accident Age: 52% had their first accident between 15–19 years.
9. Perceived High-Risk Age Groups: Highest risk seen in ages 16–20.
10. Speed Limit Compliance: 55% sometimes exceed speed limits.
11. Traffic Light Obedience: 81% always obey traffic lights.
12. Driving While Fatigued: 66% drive even when fatigued.
13. Seatbelt Usage: 55% regularly wear seatbelts.
14. Other Driving Behaviors: Includes phone usage and eating while driving.
15. Child Safety: 70% don't use a car seat for children.
16. Causes of Accidents: Speeding (86%) seen as the top cause.
17. Traffic Awareness: 82% favor mandatory Traffic Awareness courses; social media is seen as key for awareness promotion.

Implications and Insights

This analysis offers crucial insights into the traffic safety perceptions and behaviors within the university community. It highlights the necessity of interventions focused on young drivers to improve traffic safety awareness. The identification of speeding and distractions as primary accident causes emphasizes the need for behavioral change and compliance with safety standards. These findings are instrumental in shaping customized traffic safety initiatives and campaigns at the university to decrease accidents and foster a road safety culture.

3.2 Examination of Relationships and Analytical Approaches

This study utilized chi-square tests to analyze associations between categorical variables, such as age, income, driving habits, and attitudes towards traffic safety, in relation to reported traffic accidents.

1. **Demographic and Behavioral Correlations**: The study initially examined demographic factors (age, marital status) and driving behaviors (speed limit adherence, seatbelt usage), identifying behavioral patterns linked to traffic incidents.
2. **Perceptual Analysis**: It also explored participants' perceptions, including their views on the effectiveness of traffic awareness campaigns and causes of teenage driving accidents, and how these relate to their accident experiences.
3. **Statistical Significance and Interpretation**: The strength of each association was measured using chi-square statistics, with p-values below 0.05 indicating statistical significance. These significant correlations are important for further investigation and analysis.

4 Results and Discussion

This study sought to uncover the intricate relationships between individual driving behaviors, demographic characteristics, and perceptions related to traffic safety and accident occurrences. Utilizing chi-square statistical analysis, the research aimed to identify significant correlations that could provide actionable insights into enhancing road safety within the university milieu. This section presents the key relationships and their Implications derived from the chi-square, offering a nuanced understanding of the factors contributing to traffic safety and the potential avenues for intervention.

4.1 Chi-Square Statistic

This study used chi-square tests to examine the relationships between driving behaviors, demographics, and traffic accidents at the German Jordanian University. The chi-square statistic in Table 2 measures the strength of these associations, while the p-value determines their significance.

Table 2. Chi-Square Statistic

Test	Chi-Square	p-value	Significant
Age vs Seatbelt Usage	4.88	0.559	No
Education vs Seatbelt Usage	8.30	0.405	No
Age vs Phone Usage While Driving	7.67	0.263	No
Education vs Phone Usage While Driving	7.98	0.435	No
Age vs Exceeding the Speed Limit	**29.34**	**<0.05**	**Yes**
Age vs Accidents	11.28	0.080	No
Income vs Accidents	**17.41**	**<0.05**	**Yes**
Position vs Accidents	15.32	0.64	No
Phone Usage vs Accidents	1.94	0.75	No
Headphone Usage vs Accidents	8.86	0.065	No
Sitting Properly vs Accidents	6.86	0.143	No
Fatigue Driving vs Accidents	3.37	0.186	No
Speeding vs Accidents	9.79	<0.05	Yes
License Age vs Accidents	11.22	0.082	No
Opinions on when most accidents occur vs Accidents	18.38	<0.05	Yes
Vehicle Ownership vs Accidents	8.76	<0.05	Yes
Drinking While Driving vs Accidents	9.70	<0.05	Yes
Frequency of Car Maintenance vs Accidents	9.63	<0.05	Yes
Type of car insurance vs Accidents	3.62	0.459	No

The study highlights several key relationships with implications for traffic safety:

1. Demographic Factors and Accident Frequency: There are significant correlations between certain demographic variables and the frequency of traffic accidents, emphasizing the need to consider these factors in designing traffic safety measures and educational programs.

2. Driving Behaviors and Safety: Specific driving behaviors, such as speeding and adherence to safety practices, show a significant relationship with accident occurrences.
3. Perceptions of Traffic Safety: The research also explores participants' perceptions of traffic safety, including opinions on effective awareness methods and common accident causes. This provides valuable insights into the community's awareness and attitudes, crucial for developing effective awareness campaigns.
4. Vehicle Ownership and Insurance: The study found no significant statistical relationship between vehicle ownership, insurance type, and accident frequency, indicating these factors may not directly impact accident likelihood in the university community.

The study found that speeding plays a significant role in traffic accidents. While safety measures like seatbelt use are well known, targeted education on practical behavior-focused traffic safety is needed to address the gap between knowledge and behavior. It's crucial to develop age-specific and behavior-focused safety initiatives for universities. Social media is an effective tool for promoting traffic awareness among young people, providing insights for future campaign designs.

4.2 Traffic Awareness at German Jordanian University

The survey analysis from the German Jordanian University provides several key findings regarding traffic awareness:

1. Risk Perception: Respondents identified speeding, mobile phone use, and not wearing seatbelts as major risk factors in traffic accidents, underscoring the importance of these issues in traffic safety education.
2. Demographics and Traffic Safety: Links between demographic factors like income and vehicle ownership with traffic accidents and safety perceptions suggest that targeted safety initiatives for specific groups could be more effective.
3. Traffic Awareness Strategies: The prevalent belief in the effectiveness of social media for traffic awareness promotion points to the potential of digital platforms in university-targeted traffic safety campaigns.
4. Behavioral Gaps: Despite awareness of risks, the lack of a significant correlation between this knowledge and reduced accident frequency in certain areas (e.g., seatbelt usage) suggests a gap between awareness and safer behavior, indicating a need for more practical, behavior-focused education.
5. Policy Recommendations: Insights on the perceived effectiveness of social media and demographic-specific risks should inform the university's development of more targeted and effective traffic safety policies and educational programs.

5 Conclusions and Recommendations

In conclusion, the survey responses from the German Jordanian University indicate a reasonable level of traffic awareness among participants, particularly regarding the identification of risky behaviors. However, there is room for improvement in translating this awareness into safer driving practices. Tailored educational initiatives and effective use of social media could enhance the impact of traffic safety campaigns within the university community. This research contributes valuable insights into the factors influencing traffic safety within the university community. The statistically significant relationships identified offer a foundation for developing tailored traffic safety programs and policies. Future research should focus on longitudinal studies to track changes in driving behaviors and attitudes over time, further enhancing the understanding of traffic safety dynamics within similar communities.

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Analysis of the Pavement Response with Total/Partial Link Between Layers to the Action of Traffic Load

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Abstract. The paper investigates the response of the pavement of a road sector analyzed to the traffic load that was determined numerically by using Abaqus numerical modelling software. This tool offers advanced analysis options in comparison with the normative road structure dimensioning tool. Thus, in contrast to the current use road structure dimensioning program, the FEM software allows the definition of the interfaces between layers and switch loads from static load to moving load, based on the determination of the resilient stresses and deformations in road structures by using the classical linear elastic multilayer model. The aim of this study was to determine whether the road pavement with deficiencies of adhesion between asphalt layers can take over the calculated traffic load considered in the study, or the proportion of design traffic load that can be taken over. That would allow an assessment of the service operation life of the road pavement and, implicitly, of the possibility of its yielding before the end of the perspective period considered.

Keywords: Traffic · Static Load · Resilient Stresses · Perspective Period

1 Introduction

In general, the structure of asphalt pavement is made up of layers laid one over the another. Bituminous materials of many types can be used to create the layers. For both private and commercial public users, the main purpose of the road pavements is to offer a strong, comfortable, and secure traveling surface in all weather circumstances. Over the course of its design life, a well-built pavement structure should be able to deliver these structural and functional qualities with the least maintenance.

Numerous researchers have shown the impact of interlayer bonding on pavement durability through experimentation and numerical simulations [1, 2]. To keep the asphalt structure monolithic and extend its service life, adequate bonding between the asphalt layers is required. The service life of the pavement is shortened if the connection between the layers is insufficiently strong and the pavement layers work independently. However, the pavement may instantly fail due to heavy traffic. The RILEM Technical Committee

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206-ATB [3] and [4] state-of-the-art reports indicate that the following factors could affect the bonding between road asphalt layers:

- the climate at the time the pavement is cast. As a general rule, the difference in temperature between the top and lower layers plays an important role;
- reduced interlayer bonding can be caused by contamination, the presence of dirt as dust or oil from milling or construction traffic on top of the bottom layer [4, 5];
- the water flow between the layers; in comparison to dry conditions, water flow in the pavement causes a decrease of interlayer resistance due to surface cracking [6, 7];
- absence of bituminous emulsion at the interface of the two layers [8].

The connection between pavement layers can be strengthened by a variety of approaches. Chemical bonding (tack coatings, emulsions) and mechanical bonding (milling, tinning, etc.) are two ways to improve bonding [9].

As shown in Fig. 1, the function of each layer in the flexible pavement structure is to reduce and dissipate the stresses to a level that the layer below can support.

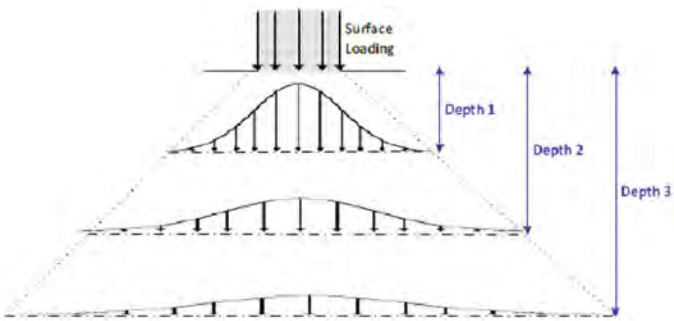

Fig. 1. Relative strength of the vertical stresses caused by the load at different depths [10].

A wide range of approaches have been proposed by numerous studies for evaluating the strength of the link between pavement layers. In the 1970s, the interface bond strength between pavement layers containing penetration-grade bitumen as a tack coat at various temperatures was measured using a direct shear test known as an interface shear mold [11]. Uzan et al. [12] proposed a systematic test method (direct shear test) for evaluating the bond shear strength between the layers having stress-absorbing interlayers. Swiss Federal Laboratories for Materials Testing and Research produced a standard technique (Swiss Standard SN 671 961) for obtaining bond strength using a Swiss LPDS tester throughout Europe [13]. Torsion tests were also recommended by Roffe et al. [13] as a method of assessing interface bond strength. Using the Superpave Shear Tester, it was examined the interface between layers using different types of tack coats, application rates and temperature conditions [14]. A basic direct shear device was created by the Florida Department of Transportation (FDOT) and can be tested with Marshall Stability apparatus or a Universal Testing Machine (UTM) [15]. To evaluate the shear properties of the interface under various surface and temperature conditions, the Ancona Shear Testing Research and Analysis (ASTRA) equipment was developed in Italy [16].

Finite element (FE) software systems, such as Abaqus, introduced in the mid-1990s, provide additional options for pavement simulation. It has been demonstrated that Abaqus can be used to solve challenging pavement issues.

2 Case-Study

The road sector analyzed is a county road in Romania with climate type I, hydrological regime 2a, and foundation soil type P5. Table 1 shows the layers of the road structure of the investigated road sector, namely the deformability characteristics of the asphalt mixtures and the foundation layers; E - dynamic modulus of elasticity and μ - the Poisson coefficient and the bulk density of each layer, according to the Romanian norm PD 177 [17]. Considering the mentioned characteristics, the pavement subjected to design is a flexible pavement designed as a multi-layer system.

The analyses presented herein show the importance of the connection degree between the layers of the road structure by examining its reaction to traffic loads. The traffic loads have an imposed value of 0.90 m.s.a. The numerical investigations were employed to examine two dimensioning hypotheses: (i) the hypothesis of perfectly bound layers and respectively (ii) the hypothesis of semi-bonded layers.

Table 1. Pavement subject to design.

Layers	h (cm)	E (MPa)	μ (−)	Bulk density (g/cm^3)
Wearing course: BA 16	4.00	3600	0.35	2500
Binder course: BAD 22.4	6.00	3000	0.35	2500
Subbase layer: Crushed stone	20.00	400	0.27	3000
Subbase layer: Gravel	20.00	152	0.27	1700
Foundation layer: P5 soil	∞	70	0.42	2800

3 Numerical Model

To model the road section, a 3D model was built by using the finite elements program Abaqus, in order to follow, with more precision, the distribution of the strains in the entire pavement layers (especially in the bituminous layers), in different bound hypothesis. The dimensions of the modelled elements (in plan) are the following: 1000 mm length × 500 mm width × 1500 mm height (for the complete model). Figure 2 shows the general geometry of the pavement layers used in the analyses.

The bottom surface of the foundation layer and the sides of the other layers are fixed tying the nodes in horizontal and vertical directions. Modelling the interaction between the layers of the road structure was done by considering a surface-to-surface-contact interaction.

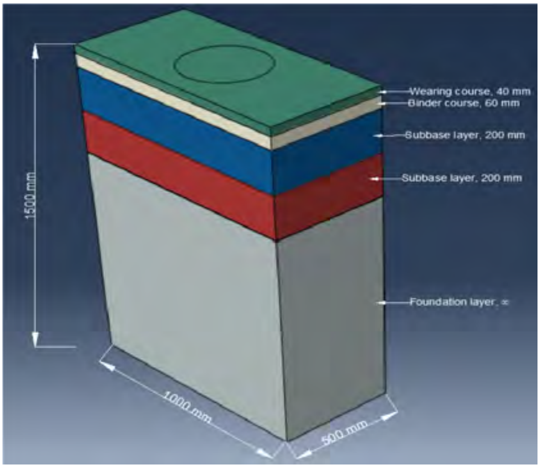

Fig. 2. Road pavement geometry.

The layers of the analyzed road structure with high dynamic modulus of elasticity values were considered as master surfaces. Those with lower values of dynamic modulus of elasticity were considered slave surfaces. The interaction between layers was influenced by a friction coefficient considering a unitary value in the hypothesis of perfectly bonded layers and 0.5 in the hypothesis of semi-bonded layers between the wearing course and the binder course.

The load considered in the analyses is introduced according to the Romanian standard 115 kN axle, which has the following characteristics:

- static load applied on twin wheels: 57.5 kN;
- contact pressure: 0.625 MPa;
- radius of circular area equivalent to the tyre-to-road contact area: 0.171 m.

The analysis of the road section at standard axle stress involves the calculation of specific deformations and stresses at critical points of the road complex, characterized by a maximum stress. The following verification steps were considered in the design:

- verification of the structure in terms of vertical specific strain (ε_r) at the base of bituminous layers;
- verification of the structure in terms of vertical specific compressive strain (ε_z) at the formation level.

The 10-node quadratic tetrahedron (C3D10) finite element with reduced order numerical integration, is used to model every layer of the pavement. The solid element (C3D10) has three degrees of freedom at each node and can represent large deformation, geometric and material nonlinearity. Figure 3b shows the total mesh model. Global mesh size was 25 for each meshed layer and a maximum deviation factor with 0.1 value. Figure 3 shows the boundary conditions used in the analysis and the circular contour of the pressure load as well as the mesh FE before loading.

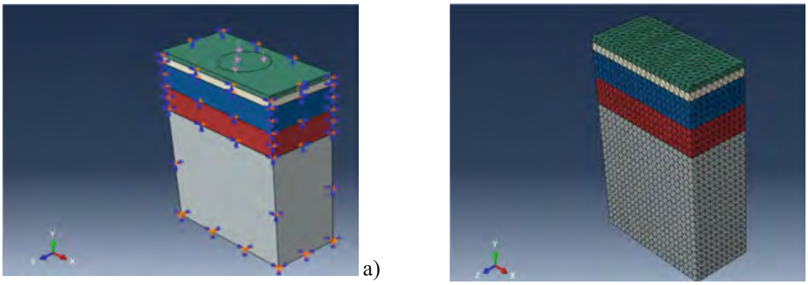

Fig. 3. (a) Load and boundary conditions; (b) Mesh model.

4 Numerical Results

4.1 Perfectly Bound Layers Hypothesis

The FE results for perfectly bound layers are shown in Fig. 4, Fig. 5 and Table 2. Units in the figures are in MPa. The admissible values (R.D.O.$_{adm}$ and ε_{zadm}) were calculated using PD 177 [17]. R.D.O. is the ratio between the design traffic in m.s.a. and the number of permissible stresses, in m.s.a., that can be supported by the bituminous layers, corresponding to the deformation state at their base.

All the FE values were compared with the values resulting from the dimensioning of the road structure analyzed by considering the Romanian road structure dimensioning program, Calderom 2000. And it appears that the deformations and stresses were identical. The results show that under the assumption of perfectly bonded layers, the checks required by the Romanian norm PD 177 [17] are fulfilled.

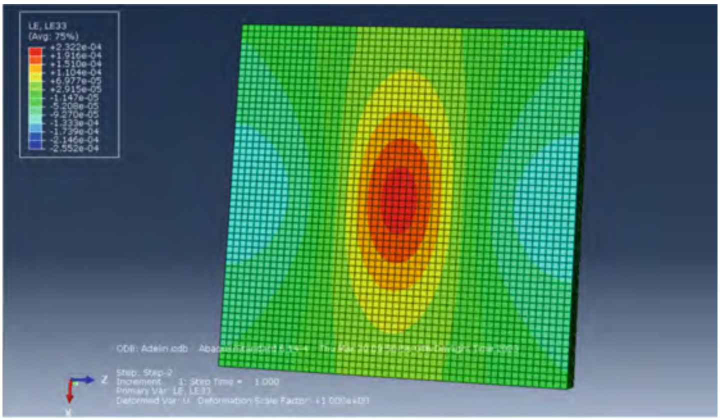

Fig. 4. Radial deformation at the base of bituminous layers.

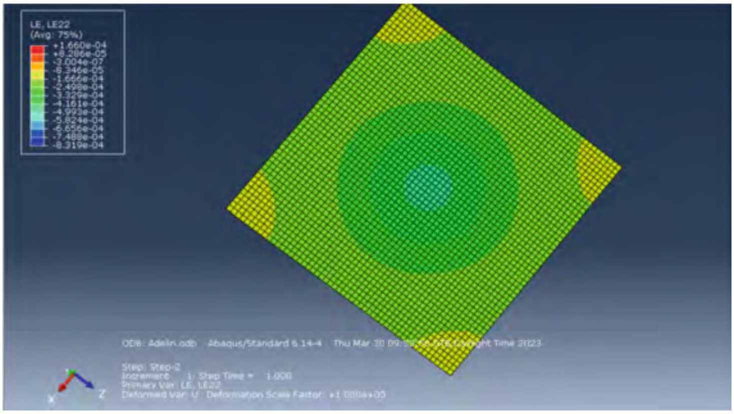

Fig. 5. Vertical specific compressive strain at the foundation ground level.

Table 2. Numerical results.

		Bonded layers	Semi-bonded layers
Design traffic	N_c (m.s.a.)	0.90	0.90
Radial deformation at the base of bituminous layers	ε_r (microstrains)	235.0	339.0
Vertical specific compressive strain at the foundation ground level	ε_z (microstrains)	574.0	716.0
Admissible vertical specific deflection	ε_{zadm} (microstrains)	618.0	618.0
Number of admissible applications	N_{adm}	0.95	0.22
Fatigue degradation rate	R.D.O	0.95	4.07
R.D.O. $_{adm}$		Max. 1.00	Max. 1.00
R.D.O $\leq$ R.D.O. $_{adm}$		Check	Don't check
$\varepsilon_z \leq \varepsilon_{zadm}$		Check	Don't check

4.2 Semi-bonded Layers Hypothesis (BA 16 50% Bonded to BAD 22.4)

For the present study, a partial bond between the BA 16 wearing course layer and the BAD 22.4 binder course was considered. This 50% bond was applied in the FE software by considering a friction coefficient of 0.5. The interaction between the other layers was "tie". Figure 6, Fig. 7 and Table 2 show the FE modelling results.

Considering the road structure according to the above condition, it was found that the R.D.O. value resulting from the modelling with semi-bonded layers does not check for the design traffic of 0.90 m.s.a. The resulting vertical strains ε_z are higher than the admissible values ε_{zadm}, The ε_{zadm} value is calculated as a function of the design traffic N_c. In these conditions, only with a designed traffic load of 0.22 m.s.a. will satisfy the criterion. This means that the initial traffic should be reduced by approximately 76%. Thus, in order to obtain an adequate design, either the design traffic should be reduced or the stratification should be thicker.

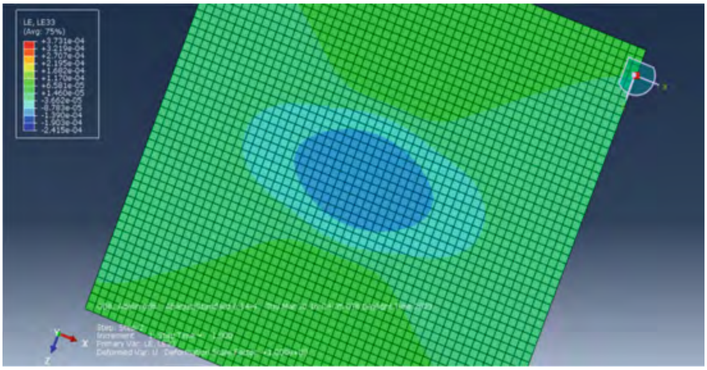

Fig. 6. Radial deformation at the base of bituminous layers.

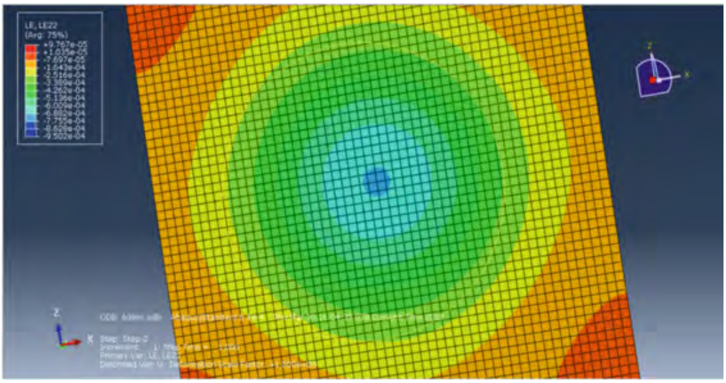

Fig. 7. Vertical specific compressive strain at the foundation ground level.

5 Conclusions

The aim of this study was to determine whether the road pavement with deficiencies of adhesion between asphalt layers can take over the calculated traffic load considered in the study, or the proportion of design traffic load that can be taken over.

The paper shows that the layer adhesion of road asphalt layers directly affects the bearing capacity of the road structures and, as a result, its service life as the number of standard axle crossings. The results show that the reduction of the connection degree between the asphalt layers to 50% leads to a reduction of the design traffic by approx. 76% as proven by the present case-study. All the values resulting from the dimensioning with semi-bonded layers check for a reduced design traffic of 0.22 m.s.a., traffic determined for a service life of 3.67 years, whether its evolution shows a consistent increase over the whole service life.

In the context of the presented study, it is of interest to evaluate other degrees of interactions, by considering different values for the friction coefficient and different type of loads (ex. Moving load together with braking force).

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Thermal-Structural Modelling and Temperature Control of Roller-Compacted Concrete Gravity Dam: A Parametric Study

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Abstract. This research is a Parametric study that investigates the temperature and thermal stress distributions in Roller Compacted Concrete (RCC) dams. The analysis used in this study involved the RCC placement temperature, the Modulus of Elasticity, tensile strain capacity, the placement schedule of RCC layers, the number of layers, and the thickness of each layer. The Metolong Dam Project in the South African state of Lesotho is used in this research as a case study, in addition to ANSYS, a well-known computer code. The sensitivity of each of the parameters listed above is investigated, and the results are presented in tables and graphs. Conclusions are drawn to better understand the effect of each parameter on the temperature distribution and thermal stress in the RCC dams.

Keywords: Thermal Analysis · Structural Analysis · Temperature Control · RCC Dam · Parametric Study

1 Review and Analysis of Related Work

RCC dams consist of concrete placed at a lower water-to-cement ratio as compared to conventional concrete with the aid of compaction equipment and methodologies normally employed for earthfill placement. RCC has gained worldwide acceptance as an alternative to conventional concrete in dam construction due to the construction advantages and proven performance [6]. When RCC was first introduced in dam construction in the early 1990's, for a time it was thought that there was no problem in the temperature control of RCC because the amount of cement in RCC was much less than that in the conventional concrete. But sometime later, it was discovered that RCC still has the problem of temperature control when it is used in dam construction [9].

Mass concrete placement requires precautions to minimize cracking. During the hydration process, cement liberates a substantial amount of heat with a resulting rise of the concrete temperature. It often reaches about 40–70 °C [5], after the maximum

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temperature is reached inside the RCC dam, the latter cools down slowly to a constant temperature. This temperature variation can induce two kinds of problems. First, the heat generated creates temperature gradients between the surface and the RCC core. The resulting non-uniform temperature distribution generates undesired stresses. Second, the reduction of the global concrete temperature to the final equilibrium temperature induces volumetric changes that lead to additional stresses if the mass concrete is externally restrained [2]. These temperature gradients induce cracks in the structures, which harm their integrity, permeability, and durability.

To find the optimum construction method to avoid thermal cracks before the structure construction, numerical simulations with Finite Element Method (i.e. FEM) can be carried out and it can be checked for cracking. In a simulation, some parameters can be assumed, such as the kind of cement, mixed design of concrete, casting schedule, RCC placement temperature, and curing method, etc. [5]. Many finite element software packages can be used to predict the heat generated by the concrete. Such as ANSYS, COSMOS/M, ABAQUS and ADINA.

Several techniques are reported in the literature for designers to evaluate the thermal performance of concrete, the structural configuration, and construction requirements. These techniques range from complex three-dimensional finite element analysis methods to simple manual computation. Another research determined the thermal and structural stresses and temperature control requirements for the 60 m high Tannur RCC dam in Jordan [7]. Temperature distribution in the Al-Mujib roller compacted concrete (RCC) Gravity Dam was also investigated in another study [8]. Moreover, another study investigated the development of the Modulus of Elasticity of young RCC dams [3].

2 Location and Description of the Dam

The Metolong Dam project located in Lesotho, a landlocked country in Southern Africa, consists of an approximately 73 m high RCC gravity dam with a crest length of approximately 210 m. The dam would store an estimated 53 million m^3, and a reservoir with an upstream reach of approximately 16 km. The full supply level will be at 1671 masl.

3 Dam Wall Profile

The upstream face of the dam is vertical from El 1671 to foundation level. The stepped downstream slope is at 0.8:1 (see Fig. 1).

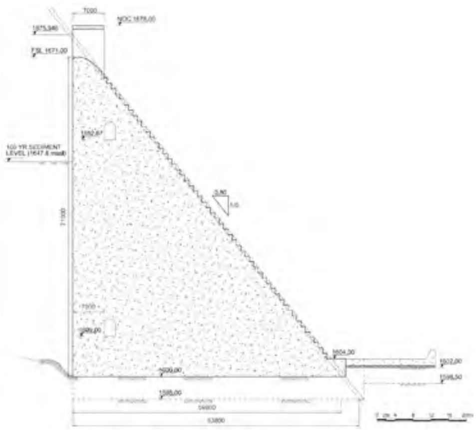


Fig. 1. Maximum cross-section of the Metolong Dam spillway.

4 Material Properties and Environmental Conditions

The model properties used were assessed from available data and typical RCC properties. The density, modulus, Poisson ratio, specific heat and thermal conductivity are given in Tables 1 and 2. A convection coefficient for air was used, which is consistent with moderate wind speed.

Table 1. Properties Adopted for Thermal Analysis for Metolong Dam.

Roller Compacted Concrete	
Density	2550 kg/m^3
Coeff. of Thermal Expansion	8.6 E-6/deg C
Specific Heat	920 J/kg deg C
Thermal Conductivity	2.15 J/s m deg C
Film (convection) Coefficient (air)	15 J/s m^2
Heat Generation of RCC	300 J/g at 28 days
Placement Temperature	18°, 20°, 24°, 28°, 30° and 32 °C
Modulus of Elasticity	22.0 GPa
Poisson's Ratio	0.2
Rock Foundation	
Density	2450 kg/m^3
Coeff. of Thermal Expansion	6.0 E-6/deg C
Specific Heat	900 J/kg deg C

(*continued*)

Table 1. (*continued*)

Roller Compacted Concrete	
Thermal Conductivity	2.15 J/s m deg C
Foundation Rock Temperature	18°
Modulus of Elasticity	14.0 GPa
Poisson's Ratio	0.3

The thermal expansion coefficient is another property used in the analysis on thermal stress in concrete. A typical coefficient of thermal expansion of 8.6×10^{-6}/deg C, was adopted for the concrete.

Table 2. Specific Parameters used in the Analysis.

Dam Properties	Reference Case	Parameters				
Placement Temperature [^{o}C]	20	18	24	28	30	32
Modulus of Elasticity [GPa]	22	20	25	–	–	–
Tensile Strain Capacity [μmm]	60	50	70	–	–	–
Placement Schedule of RCC Layers [days/layer]	10	15	20	–	–	–
Thickness of Each Layers [m]	3	2.5	3.5	–	–	–

5 Methodology

The dam is to be modeled as a two-dimensional transient heat transfer model using a birth and death element (see Fig. 2) to simulate the real construction process of the dam. The computer program ANSYS was to be used to simulate the construction process. PLANE77 thermal element type available in ANSYS element library was used. Each element has one degree of freedom temperature at each of its 8 nodes to simulate irregular shape and is applicable to a two-dimensional steady-state or transient thermal plain strain analysis. Plane strain is the condition for which the strains perpendicular to the plane of the analysis are maintained at zero. Temperatures calculated in the thermal model were used as loads for the structural model. The thermal time steps were aligned to those of the structural model. Thermal structural analysis was carried out by replacing the PLANE77 thermal element by an equivalent structural element called PLANE183 see Fig. 3. Gravity loads due to self - weight of the rock foundation and the RCC and thermal loads from thermal analysis were included in the structural analysis. Figure 4 shows only the finite element mesh for the cross sections of the dam (non-overspill section) with a 3 m layer thickness. Non-linearity of modulus of elasticity in structural analysis regarding its temporal variability is to be included in this analysis. The model developed by Conrad et al. (2003) will be used to study the effect of variation of elastic modulus with time for the RCC dam [3]. At an early age, the RCC temperature would vary significantly due to the heat of hydration, and the corresponding large strains would generate significant stresses depending on the elastic modulus. In the numerical analysis the change in the modulus of elasticity with time for RCC is incorporated according to the following equation:

$$E(t) = E_{max}\, x \exp\left(a\, x\, t^{b}\right) \tag{1}$$

where a and b are model parameters, equal to –5 and –0.63, respectively. t is the time [3]. For thermal and structural analysis, the full Newton-Raphson method with adaptive descent is used to solve the non-linear equations. Automatic time stepping is used to increase the number of sub- steps when convergence is not occurring within a given number of equilibrium iterations. When convergence occurs rapidly the number of sub-steps decreases to speed run-time. The non-linear solution control functions are implicit in ANSYS, and default parameters were used as well.

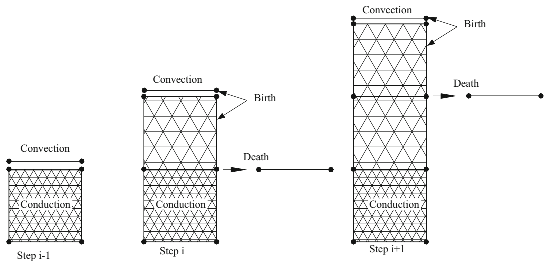


Fig. 2. Birth and death element.

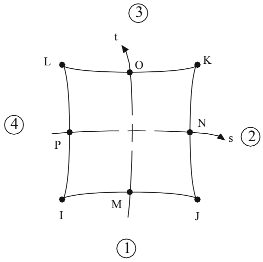
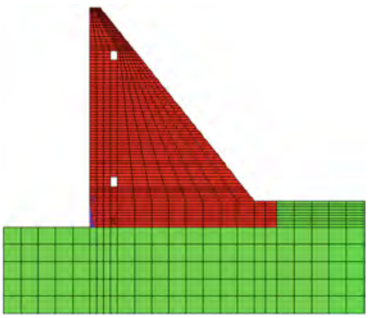


Fig. 3. PLANE77/PLANE183 element types.



- Total number of elements: 1089;
- Total number of nodes: 3492;
- Divided into 26 layers of 3m thickness.

Fig. 4. Finite element mesh of section (spillway section).

6 Effect of RCC Placement Temperature

The RCC placement temperature varied from 18 °C to 32 °C, and the temperature was calculated accordingly, it is observed that the peak temperature increases with the increasing of the RCC placement temperature. Figures 5, 6, 7, 8, 9, 10 and 11 show the variation of peak temperature development with time at different locations and elevations of the dam and its effect on the RCC Block length.

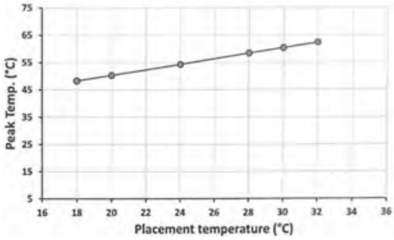


Fig. 5. Effect of placement temperature on the peak temperature in the dam.

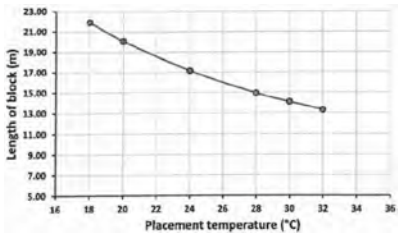


Fig. 6. Effect of placement temperature on the block length.

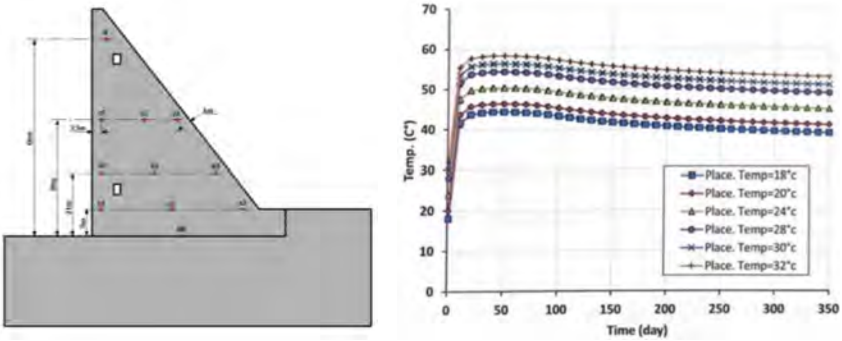


Fig. 7. Temperature time history at dam base for different placement temperature.

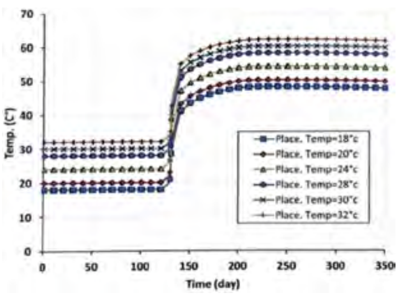


Fig. 8. Temperature time history at 21 m from dam base for different placement temperature (location b2).

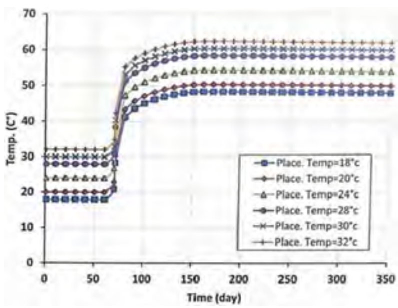


Fig. 9. Temperature time history at 39 m from dam base for different placement temperature (location c2).

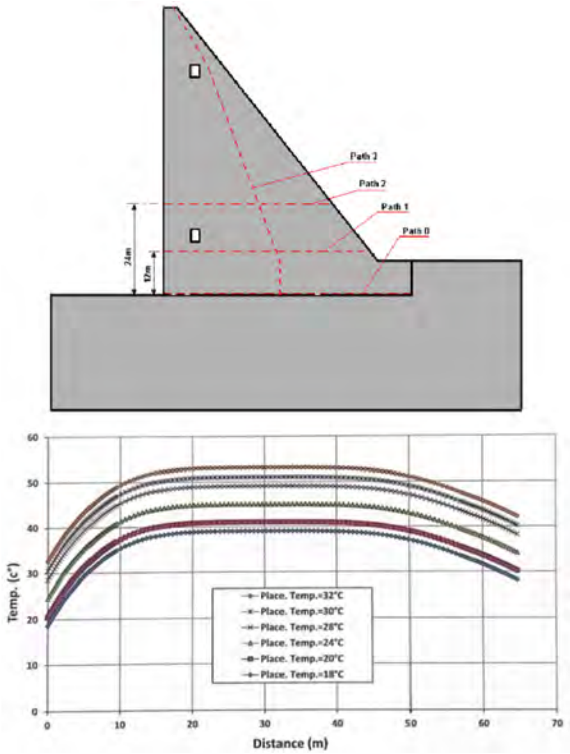


Fig. 10. Temperature distribution along dam width (path 0) at dam base at 350 days (end of hydration) for different placement temperature.

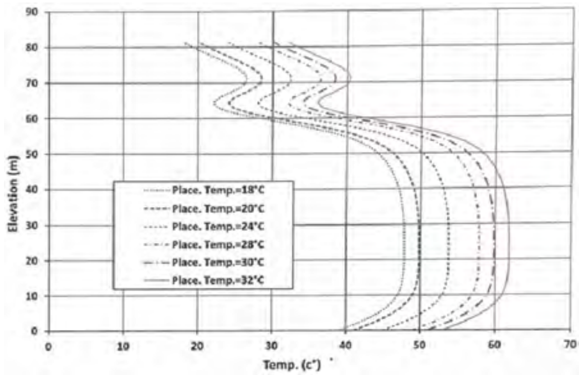


Fig. 11. Temperature distribution along dam height (path 3) at dam center at 350 days (end of hydration) for different placement temperatures.

7 Effect of RCC Young Modulus on the Thermal Stresses and Block Length

In general, the modulus of elasticity in compression is defined as the ratio of normal stress to its corresponding strain for compressive stress below the proportional elastic limit of the material (Andriolo, 1998). In this study the effect of varying the elastic Young modulus was studied, three different values were used to study the sensitivity of E with the thermal stress induced due to varying the RCC placement Temperature. Figure 12 shows the variation of RCC placement temperature with Young Modulus. Figure 13 shows their effect on the development of thermal stresses with time.

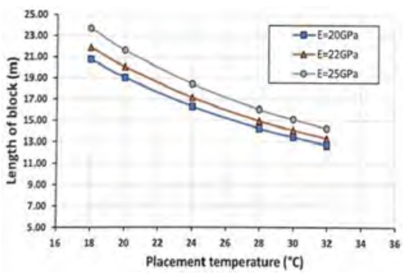


Fig. 12. Effect of RCC Young Modulus on the block length.

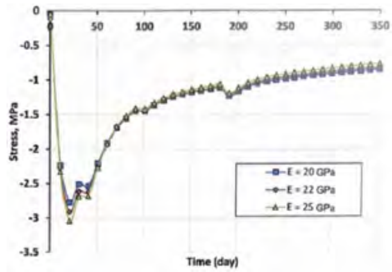


Fig. 13. Valley stress (x-direction) in the Dam base center (b0).

8 Effect of Strain Capacity

Tensile strain capacity TSC (ε_{tc}) is the change in length per unit length that can be sustained in concrete prior to cracking. TSC is dependent on time and rate of loading and many other factors among them are type of aggregate, aggregate shape characteristics, and strength of the RCC mix. Conrad, M. (2006), introduced an empirical formula to estimate the TSC which is based on the below formula [4]. Usually, for RCC this value of TSC ranges from 20–140 × 10^{-6} mm/mm.

$$TSC = \frac{f_t}{E_{eff}} \tag{2}$$

with:

TSC = Tensile strain capacity;

f_t = Direct tensile strength (MPa);

E_{eff} = Effective Young's Modulus (MPa).

In this study, three values were used with different RCC placement Temperature see, Fig. 14 shows the effect of TSC with block length and using different RCC placement Temperature.

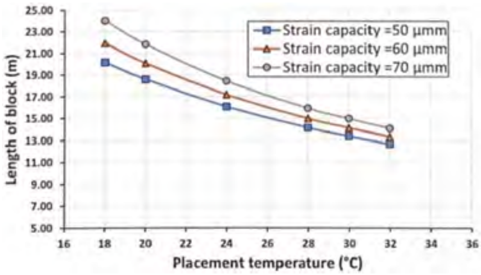


Fig. 14. Effect of Strain Capacity on the block length.

9 Effect of Layer Thickness

Usually, RCC dams are constructed in layers, each layer has thickness of 3 m constructed in 10 days. In this study the dam is modeled in three different thickness i.e., 2.5 m, 3 m and 3.5 m each constructed in 10 days. Figures 15 and 16 show the effect of layer thickness on the peak temperature and on the block length, Figs. 17 and 18 show temperature time history at different locations and elevations of the dam.

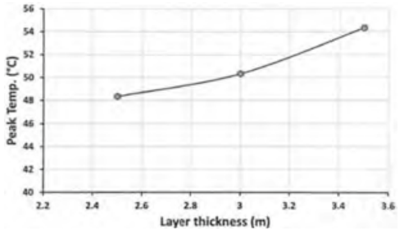


Fig. 15. Effect of layer thickness on the peak temperature in the dam.

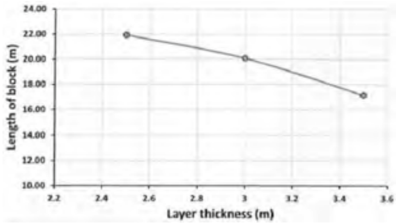


Fig. 16. Effect of layer thickness on the block length.

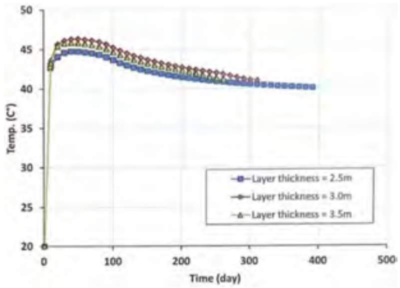


Fig. 17. Temperature time history at dam base different layer thickness

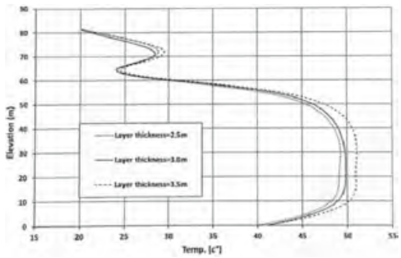


Fig. 18. Temperature distribution along dam width (path 3) at dam center at end of hydration for different layer thickness

10 Conclusions

A parametric study is carried out in this research to study the effect of several parameters affecting the temperature and thermal stress distributions in RCC dams. The RCC placement temperature, the Modulus of Elasticity, tensile strain capacity, placement schedule of RCC layers, number of layers, and thickness of each layer were all considered in the analysis. The sensitivity of each one of the parameters listed above is investigated and the results is presented in form of tables and graphs. The results presented in this study clearly demonstrate the effect of each of the studied parameters and provide a better understanding of the effect of each parameter affecting the temperature distribution and thermal stresses in the RCC dams.

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Structural Engineering

Influence of Shear Connection and End Supports onto Self-vibrations of Cold-Formed Steel Concrete Composite Floor

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Abstract. Cold-formed steel composite floors are lightweight systems whose application increased in the last few decades. According to the design guidelines, the frequency of floor systems should be more than 4 Hz while in the case of light steel floors, the natural frequency of the system should be in the high frequency range above 8 Hz. The main focus of this paper is to investigate the vibration performance of an innovative lightweight composite floor system called LWT-FLOOR. The LWT-FLOOR system is composed of spot-welded built-up cold-formed steel elements that are connected to a lightweight concrete slab. Based on laboratory tests material properties of all components of the system are obtained and the finite element model of cold-formed steel concrete composite floor is created to investigate its vibration behaviour. Numerical analyses were conducted in Abaqus/CAE, where after mesh density verification, the influence of the degree of shear connection, spot weld density, concrete type and class, steel channels cross-section thickness and the arrangement and diameter of the shear connector were analysed. The results show that the flexural rigidity of the system and vibration characteristics can be improved by changing those parameters, especially by changing steel channel cross-section characteristics and support conditions from nominally pinned to nominally rigid.

Keywords: Self-Vibrations · LWT-FLOOR Composite Beams · FE Analysis · Parametric Study

1 Introduction

According to European standards [1, 2] to achieve satisfactory vibration behaviour of buildings and their structural members under serviceability conditions aspects related to the comfort of the users and the functioning of the structure or its structural members among the aspects specified in particular National Annex should be considered. During the verification of serviceability, the structure or structural member should be kept below appropriate acceleration limits relevant to the user's comfort and functionality. For specific types of structures or structural members, the acceleration limits can be assumed to be met when the natural frequency of vibrations is kept above appropriate values. For example, the Croatian National Annex to EN 1990 [3] provides limitations of 10 Hz for

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grandstands, fitness centres, sports halls and public premises and 8 Hz for residential and office buildings. In addition to the design guidelines [4], the frequency of floor systems should be more than 4 Hz while in the case of light steel floors, the natural frequency of the system should be in the high frequency range above 8 Hz. If the natural vibration frequency of the structure or structural member is lower than the appropriate value, a more refined analysis of the dynamic response of the structure considering damping is needed.

Cold-formed steel-concrete composite systems have become more popular in the last decades and their vibration characteristics are important, especially in the case of lightweight systems. In the characterization of floor vibrations, two characteristics are important: the fundamental frequency and damping ratio. Considering that in composite steel-concrete systems, the shear connection has a great role, its influence on vibrations must be taken into consideration.

In the case where composite beams are formed using deformable connections, the dynamic solution for this kind of connection is investigated in paper [5]. The authors analysed the resulting in plane forces and deformations of the slab as well as the axial forces and deformations of the beam. The research concludes that the adopted model permits the evaluation of the time history of the in plane shear forces at the interface between the concrete slab and the beams, the knowledge of which is very important in the design of composite or prefabricated structures (with emphasis on degree and type of shear connection - shear connectors or welding). Also, great variations of the fundamental eigenfrequency with the shear connectors' stiffness are shown in the research. Furthermore, the discrepancy in the results between the proposed model and the one ignoring the in plane forces and deformations, which requires the consideration of these forces and deformations in the structural model, is more pronounced for low values of the beam height.

Another research on the influence of shear connector damage on dynamic behaviour shows that the interface slip will directly influence the integral stiffness of steel-concrete composite beam, the vertical frequencies and mode shapes [6].

Investigation in paper [7] of the influence of the shear connectors (stud bolts of 16 mm and 19 mm diameter) on the floor's natural frequencies, shows that the influence is small in the cases when the degree of shear connection goes from full shear to partial. The largest difference was up to 7%.

The investigation made by Henderson et al. [8] showed how the overall frequencies of composite specimens are higher than the non-composite section.

Furthermore, the importance and influence of shear connection to beam frequency response is also presented by Sun et al. [9]. It is concluded that stronger interfacial interaction, larger steel sub-beam and thinner concrete slab lead to higher values of the natural frequencies of a steel-concrete composite continuous beam.

A detailed description of the analytical approach to calculate vibrations of steel-concrete composite beams with partially degraded connection and applications to damage detection in structures are shown in [10]. From the research, it is concluded that the frequency variations contain information on the position of the damage.

Shen et al. [11] investigate the formulae for analysing the dynamic behaviour of composite beams with partial interaction. The research shows how to calculate the natural frequencies and the corresponding mode shapes. Also, boundary conditions can be expressed directly by proposed formulae.

Kansinally and Tsavdaridis [12] investigated vibration response of a composite floor system composed of ultra shallow floor beams. The influence of fixed and pinned boundary conditions is analysed. The research concludes that in the case of fixed boundary conditions and concrete slab thickness of 100 mm, high natural frequencies for all mode shapes are observed. In the case of pinned supports, natural frequencies for the first three mode shapes are analysed. It is concluded that natural frequencies are increased by 16–24% for pinned boundary conditions compared to fixed boundary conditions. Parabolic behaviour of natural frequencies is observed in the case of the first four modes where the slab thickness is decreased. More research on the topic of boundary conditions is shown in [13, 14].

In addition to the aforementioned, the influence of the thickness of the slab and concrete grade on composite floor vibration behaviour is investigated in paper [15]. The parametric study with different concrete grades showed negligible influence on dynamic behaviour for all analysed cases (C16/20, C25/30, C35/45, C45/55). On the other side, a great influence can be observed for slabs having small aspect ratios (1:1, 1:1.5, 1:2) by increasing the thickness of the slab.

Another investigation on the thickness of concrete slab is conducted in order to determine the minimum slab thickness of a reinforced concrete building to prevent undesirable vibration [16]. It is concluded that the floor frequency decreases with increasing floor panel aspect ratio. Furthermore, by increasing slab thickness, the floor frequency increases and by increasing span length, the floor frequency is reduced.

Considering the different parameters that can affect the natural frequencies of the system, different standards analyse the same issue in order to prevent negative consequences [17, 18]. For example, US codes and standards, which are investigated in paper [19], say that vibration serviceability criteria for floor structures are human-induced dynamic loads, human perception of structural vibrations and structural vibration control and should be checked. Thus human-induced dynamic loads are important generators of vibrations. If compared to European standards [1], it is only mentioned that the verification of serviceability limit states should consider vibrations that cause discomfort to people or that limit the functional effectiveness of the structure. Detailed analyses of the spectral modelling approach for crowd-rhythmic activities performed on steel-concrete composite floors is shown in [20] where the influence of jumping and skipping and design-oriented method is presented for a simplified evaluation of floor response for analysed rhythmic activities.

This paper investigates vibration performance on the LWT-FLOOR composite system which is described in paper [21]. The influence of the degree of shear connection, spot weld density, concrete class and type, steel cross-section thickness, the diameter of the shear connector and boundary conditions on the vibrations are analysed.

2 Numerical and Parametric Analyses

Numerical analysis is performed in Abaqus Standard software [22] using Frequency analysis. Models are formed of built-up cold-formed steel beam and concrete slab which is laid on metal sheet. The overall height of a composite steel-concrete beam is 520 mm, where the height of built-up steel beam is 400 mm. Beam length is 6 m and the concrete slab effective width is 1500 mm, as shown in Fig. 1. The model is formed of four channel height of 120 mm, while the thickness is changed (0.8 mm, 1.0 mm, 2.5 mm and 3.0 mm), four shear plates height of 400 mm and thickness of 1.0 mm and corrugated web with rib height of 60 mm, thickness of 1.0 mm and height of 400 mm. Additional boundary conditions simulating symmetry along the beam are applied along the longer edges of the concrete slab. This means that the complete model consists of two steel beams and a 3 m wide concrete slab.

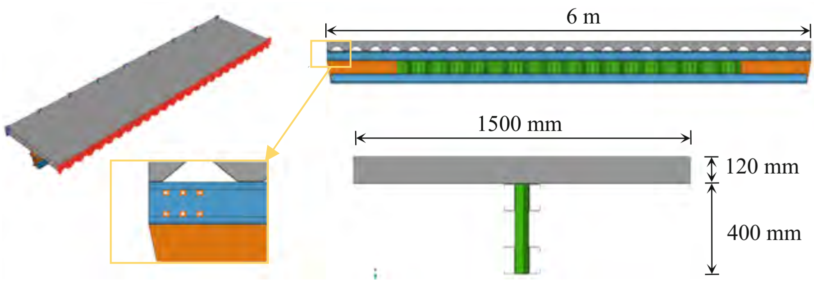


Fig. 1. Geometry and boundary conditions of LWT-FLOOR composite beam.

Imperfections are not included in the analysis so the first step before parametric frequency analysis is related to mesh density verification. The initial model based on research provided in [23] consists of finite elements and mesh densities described in the following text. Elements of steel beams are defined as S4R elements, while for concrete slabs and bolts, C3D8R elements are used. Chosen mesh size for steel elements is 15 mm, for a concrete slab is 30 mm, and for bolts is 5 mm.

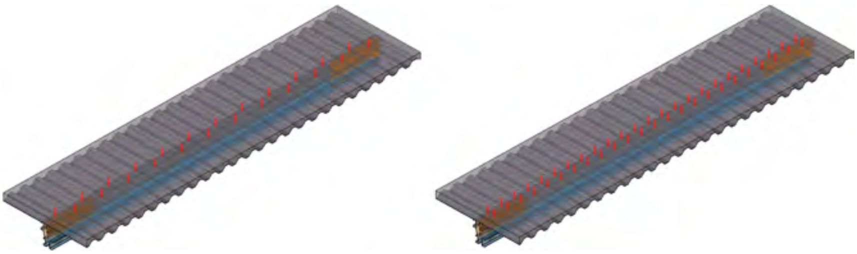
After several mesh refinement trials, the mesh size for steel elements of 10 mm, concrete slab of 15 mm and bolts of 5 mm resulted in satisfactory convergency in obtained self-vibration frequencies. The results of the mesh density study are presented in Table 1.

The steel elements are made of steel grade S350 GD whose material properties are determined by laboratory tests [24]. The concrete material properties (LC 12/13, LC 16/18, LC 20/28; NC 20/25, NC 25/30, NC 30/37) are calculated according to EN 1992-1-1 [25] and [26]. The thickness of the corrugated web and shear plates is 1.0 mm while the analysed thicknesses of the channel are 0.8 mm, 1.0 mm, 2.5 mm and 3.0 mm.

Different degrees of shear connection (SC) are analysed. The full degree of SC is achieved when a tie constraint is used between the upper flange of the C profile and metal sheet, and between metal sheet and concrete slab. On the other hand, different degrees of SC are established by the physical modelling of shear connectors. Bolts M12 (diameter of 12 mm) and M16 (diameter of 16 mm) are used as shear connectors in staggered arrangement (Fig. 2a) or arrangement in pairs (Fig. 2b).

Table 1. Mesh density study – natural frequencies [Hz].

CONCRETE SLAB					STEEL ELEMENTS				
MODE / MESH	1	2	3			1	2	3	
30	21.73	64.24	68.69		15	21.81	64.58	73.17	
15	21.81	64.58	73.17		10	21.60	63.70	72.45	
10	21.82	64.67	74.27		7	21.60	63.81	72.37	
7	21.82	64.70	75.0		5	21.51	63.42	71.96	
					2	21.51	63.38	71.98	



a. staggered b. in pairs

Fig. 2. Shear connectors arrangements.

Connection between steel elements (CbSE) is ensured by tie constraint which ties two surfaces together so that there is no relative motion between them, and by spot welds (two or three along profile height). Spot welds are defined as point-based fasteners as described in paper [27].

Table 2 shows the differences in numerical models analysed in this research. Taking into account the influence of the degree of SC, spot weld density, concrete type (CT), channel thickness (T), boundary conditions (BC) and the arrangement and diameter of the shear connectors, 26 numerical models were formed. In further text, the nomenclature "Model X-LC" is used for models with lightweight concrete (LC) and "Model X-NC" for models with normal concrete (NC) models.

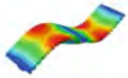
Table 2. Numerical models.

NAME		CT	T [mm]	SC	CbSE	BC
Model 1	LC	LC 16/18	2.5	tie	tie	simple
	NC	NC 25/30				
Model 2	LC	LC 16/18	2.5	in pairs – M12	tie	simple
	NC	NC 25/30				
Model 3	LC	LC 16/18	2.5	staggered – M12	tie	simple
	NC	NC 25/30				
Model 4	LC	LC 16/18	2.5	in pairs – M16	tie	simple
	NC	NC 25/30				
Model 5	LC	LC 16/18	2.5	staggered – M16	tie	simple
	NC	NC 25/30				
Model 6	LC	LC 16/18	2.5	tie	2	simple
	NC	NC 25/30				
Model 7	LC	LC 16/18	2.5	tie	3	simple
	NC	NC 25/30				
Model 8	LC	LC 12/13	2.5	tie	tie	simple
	NC	NC 20/25				
Model 9	LC	LC 20/28	2.5	tie	tie	simple
	NC	NC 30/37				
Model 10	LC	LC 16/18	3.0	tie	tie	simple
	NC	NC 25/30				
Model 11	LC	LC 16/18	1.0	tie	tie	simple
	NC	NC 25/30				
Model 12	LC	LC 16/18	0.8	tie	tie	simple
	NC	NC 25/30				
Model 13	LC	LC 16/18	2.5	tie	tie	rigid
	NC	NC 25/30				

3 Results and Discussion

Considering different influences on the natural frequencies of the LWT-FLOOR composite system, Table 3 and Table 4 show the values of natural frequencies [in Hz] for the first three modes of each model. The values of natural frequencies for the first three modes for Model 6 and Model 7 are shown separately in Table 4 because of the different mode shapes from Models presented in Table 3. Those different mode shapes are related to spot-weld connections between steel elements.

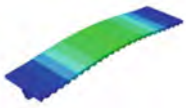
Table 3. Natural frequencies for models with tied steel elements [Hz].

MODELS \ MODES		MODE 1 	MODE 2 	MODE 3 
1	LC	21.60	63.70	72.45
	NC	19.00	57.06	80.89
2	LC	21.52	63.17	71.77
	NC	18.93	56.57	80.09
3	LC	21.20	60.39	67.55
	NC	18.61	53.78	72.92
4	LC	21.37	62.92	71.93
	NC	18.80	56.30	80.21
5	LC	21.51	63.11	71.72
	NC	18.93	56.49	80.00
8	LC	21.22	62.26	67.51
	NC	18.94	56.81	79.30
9	LC	21.63	63.81	72.86
	NC	19.06	57.28	82.28
10	LC	23.36	67.56	72.24
	NC	20.77	61.06	80.77
11	LC	15.92	49.01	73.06
	NC	13.68	42.91	75.56
12	LC	12.60	38.74	69.79
	NC	10.83	33.96	63.06
13	LC	31.50	68.60	73.81
	NC	28.60	60.97	82.35

The influence of the degree of shear connection can be observed by comparing the results of Models 1, 2 and 3. It is shown how the value of natural frequency decreases by decreasing the degree of shear connection. Furthermore, observing the results of models with the same arrangement of shear connectors and different diameters (Model 2-Model 4; Model 3-Model 5), it is concluded that, models with shear connector diameter of 12 mm achieve higher frequency for modes 1 and 2. However, for mode 3, models with a shear connector diameter of 16 mm achieve higher frequency than models with a shear connector diameter of 12 mm. Analysis of models with different concrete classes (Model 1, Model 8, Model 9) shows that by increasing concrete class, the value of natural frequency increases as well. Furthermore, comparing the results of models marked by LC and NC of the same model number, it is concluded that models formed of NC have lower frequency levels of modes 1 and 2 than those formed from LC, while for mode 3 the opposite occurs. Furthermore, by analysing the influence of the different thicknesses of the channel steel section, it is concluded that the level of frequency increases in the first two modes when increasing the thickness of the channel section. Also, comparing results for Models 1 and 13 where different boundary conditions are defined, it is concluded that by changing boundary conditions from nominally simple to nominally pinned, the natural frequency is increased.

In Table 4, modes and values of natural frequencies are shown for models where steel parts are connected using two (Model 6) and three (Model 7) spot welds. These models do not have the same behaviour for the first three modes as models in Table 3 because of the local mode shapes of the steel girder. Neglecting local mode shapes Table 4 shows global modes, i.e. modes 1, 4 and 7.

Table 4. Natural frequencies of Models 6 and 7 with spot welded steel elements [Hz].

MODES / MODELS		MODE 1	MODE 4	MODE 7
				
6	LC	17.66	43.32	64.017
	NC	15.64	38.96	65.57
7	LC	17.69	43.38	64.73
	NC	15.67	39.00	66.38

From the results presented in Table 4, it is concluded that a larger number of spot welds cause a higher natural frequency of the system. This is expected due to the increased stiffness of the system.

4 Conclusions

In this study, the influence of several parameters on natural frequencies of cold-formed steel–concrete composite floor system LWT-FLOOR level is investigated. Varying parameters are the degree of shear connection, shear connector diameter, spot weld density, concrete type, steel cross-section thickness, and boundary conditions.

From all presented results, it can be concluded that by increasing all analysed parameters (the degree of shear connection, shear connector diameter, spot weld density, steel cross-section thickness) and by choosing the greater class of concrete and changing boundary conditions from nominally simple to nominally pinned, the level of natural frequency is increased.

Analysing the degree of shear connection in vibration behaviour, it is shown that the value of natural frequency decreases by decreasing the degree of shear connection. Furthermore, by increasing the diameter of the shear connector, the natural frequencies decrease for the first two modes, but in the third mode, the frequency for models with larger shear connector diameters achieves a higher value.

Changing concrete classes shows that by increasing concrete class, the value of natural frequency increases as well. Furthermore, comparing models with lightweight concrete and normal concrete, it is shown that models with normal concrete have lower frequency levels than those with lightweight concrete (for modes 1 and 2). Furthermore, authors concluded that the level of frequency increases in the first two modes when increasing the thickness of the channel section. Also, by changing boundary conditions from nominally pinned to nominally rigid, the natural frequency is increased.

Furthermore, it is shown that the LWT-FLOOR composite floor system for all analysed cases has a frequency in the range from 15 Hz to 31 Hz which is higher than the 4 Hz required by literature and classifies the analysed system in the category of applicable floor structures according to the level of vibrations.

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Numerical Investigation of Double-Skin Cold-Formed Steel Shear Wall Filled with Concrete

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Abstract. Steel and composite shear wall systems are used for vertical stabilisation of buildings and have been widely investigated in recent decades. Such systems provide excellent shear strength and ductility while allowing material savings due to optimal material usage and an increase in construction speed. A double-skin cold-formed steel shear wall filled with concrete is an innovative composite shear wall that is composed of cold-formed corrugated steel sheets and intermediate fasteners filled with concrete which is in turn bounded by a steel frame. Steel sheets are connected onto a concrete core with the help of intermediate fasteners behaving as shear connectors forming a sandwich Steel–Concrete–Steel panel. Compared to reinforced concrete shear walls, this type of wall has enhanced strength and ductility due to steel confinement while allowing for a reduction in construction time. The numerical simulation of double-skin cold-formed steel shear walls filled with concrete has been studied in this paper. The numerical parametric simulations are conducted in ABAQUS/CAE, where the influence of steel sheet thicknesses, concrete strength and the arrangement and diameter of the shear connectors were analysed. The wall shear capacities for all parameters were compared and the results provide suggestions for future investigations.

Keywords: Cold-formed steel · shear wall · corrugated steel sheeting · double-skin · composite systems · monotonic load

1 Introduction

In recent years, light-framed cold-formed steel (CFS) structures have been widely used in North America, Australia and Japan, particularly for low and medium-rise buildings. The CFS system is rightly being more popular precisely because of the numerous advantages that characterise it. Such lightweight systems in particular are considered to be cost-effective systems that offer convenient modular design, high strength, efficient mechanical assembly, recyclable components and good seismic behaviour [1–4]. Due to the significant structural and ecological efficiency of CFS lightweight structures, research interest has increased significantly in improving the behaviour of such systems in high seismic areas for mid-rise and high-rise buildings. However, the lack of such a system in mid-rise and high-rise buildings is precisely the insufficient lateral resistance

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to absorb horizontal forces due to earthquakes or strong winds [5]. Therefore, the shear walls are an indispensable part of such CFS building systems because they are primarily lateral force-resisting elements that also transfer the vertical load [6, 7]. Through various research and practises, there are numerous types of sheeting, including gypsum board, cement particle board, plywood, oriented strand board (OSB), steel sheets and corrugated web.

The beginnings of research into the behaviour of CFS shear walls were started by Fülöp and Dubina [8]. As part of this research, a series of full-scale monotonic and cyclic tests of shear walls with different types of sheeting materials such as corrugated steel sheets, OSB and gypsum board were carried out. The research has shown that the failure of corrugated shear walls is due to damage to the seam fasteners and subsequent failure of the corrugated panel. However, it was ultimately concluded that CFS shear walls with corrugated sheeting exhibit a rigid behaviour and can effectively resist lateral loads. The researchers also suggested increasing the load-bearing capacity and ductility of the seams fasteners to improve the performance of the shear wall. A more extensive study was carried out by Stojadinavić and Tipping [9], in which a series of 44 tests were performed on CFS shear walls with corrugated steel sheeting. In the tests, a total of six parameters varied between samples, such as the geometry of the profile and corrugated sheeting, the type, size and spacing of the fasteners, the inclusion of additional gypsum boards on one side and the application of single-skin or double-skin corrugated sheeting on the side of the CFS shear walls. In the end, the researchers concluded that in all samples, the fasteners were pulled out through the wrap of the corrugated sheeting, creating diagonal tension and compressive areas. The continuation of this research was conducted by Yu et al. [10], where the influence of the thickness of the frame members, the size and spacing of the fasteners and the configuration of the boundary members on the behaviour of CFS shear walls was investigated. In the studies by Yu et al. [10] and Zhang et al. [11–13], a corrugated steel sheeting is attached to the surface of the CFS frame elements. Such a shear wall configuration has shown good behaviour with high strength and stiffness. Furthermore, based on the research on the behaviour of CFS shear walls with corrugated steel sheet, it was concluded that corrugated sheet has higher strength and stiffness compared to some conventional sheets such as flat steel sheets, wood panels and OSB. However, the results of the study by Fülöp and Dubina [8] show that the loading method has no significant effect on the stiffness of the CFS shear wall, but the ductility of the wall is slightly lower under cyclic loading than under monotonic loading. This behaviour is caused by the failure of the fasteners to the corrugated sheet. To improve the behaviour of the wall in this respect, a series of tests using corrugated sheets with different types of openings were conducted [14, 15]. The idea of corrugated sheeting with openings allows for localised weakening of the sheeting stiffness and at the same time out-of-plane buckling and tearing of the panel around the opening. At the same time, it is assumed that there will be no sudden drop in the shear strength of the wall and an increase in the capacity for energy dissipation under cyclic loading is expected. Such a change in force transmission can prevent or partially reduce the failure of fasteners. In the study [14, 15], circular holes and slit openings were investigated and in the end, it turned out that the proper slit openings in the sheeting provided satisfactory ductility of the shear wall while maintaining significant strength and initial stiffness. Furthermore, research on the behaviour of lateral resisting systems has shown that the application of a concrete layer allows a more even distribution of stress in steel shear walls. Such behaviour improves the system performance and leads to maximum utilisation of the shear capacity of the shear wall [16, 17].

This research aims to develop the idea of the moment-resistant frame with an innovative bracing system such as a CFS shear wall with double-skin corrugated sheeting with an intermediate concrete layer. Such a system could potentially be used in high seismic areas for medium-rise and high-rise buildings, as the energy can be dissipated at the designated locations and the shear walls can be replaced, which would reduce repair costs. This paper provides a preliminary insight into the behaviour of a CFS shear wall with a double-skin corrugated sheeting with an intermediate concrete layer (DCSWC). Finite element analysis was used to validate the model of the CFS shear wall with single-skin corrugated sheeting according to the tests [18], which will then serve as a benchmark model for the development of the model with a double-skin concrete layer.

2 Finite Element Modelling

2.1 Development of FE Models

The finite element analysis was performed with the Abaqus Explicit Solver to cover geometric and material nonlinearities. The finite element modelling method used in this study is similar to that of Mahdavian [18]. The shear wall with the dimensions of 2.4 $\times$ 1.2 m consists of vertical framing members with a cross-section of 350 S 200-68, horizontal framing members with a cross-section of 350 T 150-68 and the corrugated steel sheeting Verco Decking SV36, as shown in Fig. 1. Given that the study [18] does not explicitly address any imperfections, they have not been incorporated into the numerical model. The material properties of the CFS elements are defined by the bilinear elastic-plastic material model. The general parameters of the material model are the modulus of elasticity and Poisson's ratio, which were assumed to be 203.4 GPa and 0.3, respectively. True stress-strain curves were adopted based on experimental test results of the CFS base material [18]. The connection between the corrugated steel sheeting and framing members is achieved using screws. The connection between two sheetings is also made in the same way, considering that the shear wall consists of three sheetings over its height. In the numerical model, the simulation of the behaviour of the screws was realised with the Connector Builder through the implementation of the corresponding connector section. For the corresponding connection, screw stiffness is defined in the vertical and horizontal directions based on the connection test results provided in [18]. However, since no failure occurred in the connections between the frame members, tie constraints were assumed for stud-to-stud and stud-to-track connections. The boundary conditions are simplified compared to the experimental samples. Therefore, displacements and rotations in all three directions are prevented at all points of the web of the bottom track as well as the bottom contour of the cross-section of the studs. The hold-down area of each chord stud is simulated in such a way that vertical displacements are prevented at all points in this area. To ensure that out-of-plane displacement of the shear wall does not occur, out-of-plane displacements were prevented at the points of the upper track flanges to simulate lateral support in the actual experiment. In addition, all points of the web of the upper track are connected to the coupling constraints with a reference point. The reference point is located at the edge of the top track through which the horizontal load application was realized using the displacement control method. The interaction between sheeting and framing members is defined by surface-to-surface contact, using normal and tangential behaviour. The definition of normal behaviour (hard contact) prevents penetration of the sheeting through the frame members or vice versa, while tangential behaviour is simulated using the penalty frictionless method. All parts of the model were modelled using shell elements (S4R). The global mesh size is 38 mm for the corrugated sheeting and 12 mm for the framing members (studs and tracks).

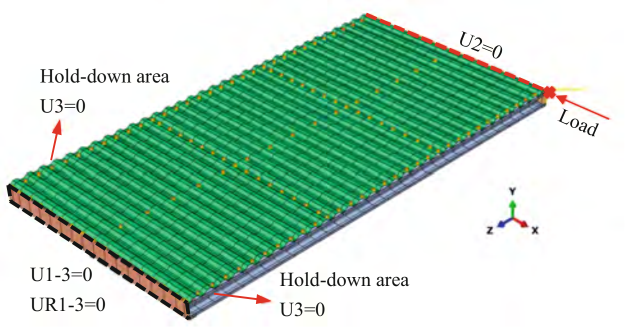


Fig. 1. Numerical model based on Test 54 by Mahdavian [18].

As already mentioned, the model from Fig. 1 will serve as a benchmark model for modelling a double-skin CFS shear wall filled with concrete (DCSWC). The DCSWC model contains a profiled sheeting on both sides of the CFS frame, between which a concrete layer is embedded, as shown in Fig. 2. The modelling of the connection of the sheeting and framing members is adopted as in the benchmark model, while the connection of the double-skin sheeting through the concrete is realised using bolts. The positions of the bolts are shown in Fig. 2. The bolts are modelled as beam elements (B-31) with associated material properties such as yield strength and strength, whose values are 240 and 400 MPa. To simulate the behaviour of the concrete wall, the CDP model was used, for which the plasticity parameters were assumed as in [19]. Furthermore, the bolts and the individual framing members were embedded in the concrete wall to simulate the contact between bolts and CFS elements with concrete. The bolts were attached to the corrugated sheeting with the "MPC tie" constraint. To simulate the contact between concrete and corrugated sheets, surface contacts were used that define the normal behaviour and the tangential behaviour with a friction coefficient of 0.15. In addition, the general contact was used for whole model to consider any new contact arise during the analysis. For the general contact, the contact property with normal and tangential behaviour was used, assuming a friction coefficient as frictionless. The concrete slab was modelled with a solid element (C3D8R), using a global mesh of 30 mm.

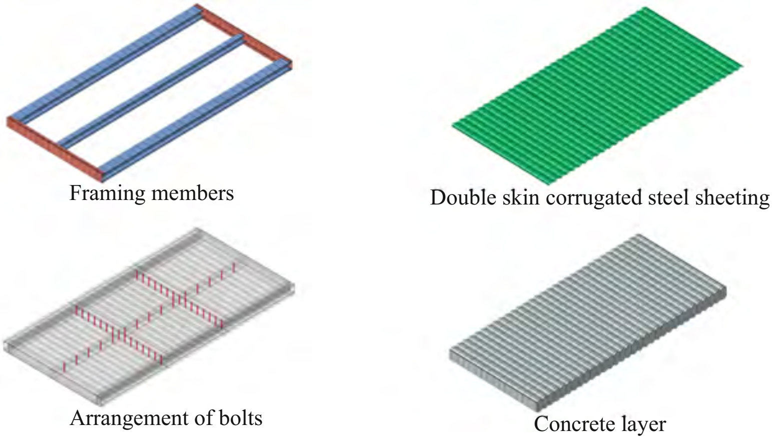


Fig. 2. Components of the model of double skin CFS shear wall filled with concrete.

2.2 Model Validation

The results of the numerical analysis were compared with the experimental results of Test 54 by Mahdavian [18] to establish a validated model. The numerical load-displacement curve shows a good agreement with the experimental curve, as shown in Fig. 3. Also, the compared characteristic values are shown in Table 1.

Fig. 3. Comparison of experimental and numerical curve.

Table 1. Comparison of experimental and numerical results.

	P_{ult} [kN]	Ratio	Δ_{ult} [mm]	Ratio
Experimental	80.8	**0.92**	68.4	**1.00**
Numerical	73.9		68.5	

Furthermore, a detailed investigation of the numerical model revealed buckling of the corrugated sheeting in the bottom zone of the shear wall accompanied by slight torsional and localised buckling of the vertical framing members. These failure modes were also observed in experimental tests, as shown in Fig. 4. Therefore, this model was used as a benchmark model to model a double-skin cold-formed steel shear wall filled with concrete (DCSWC).

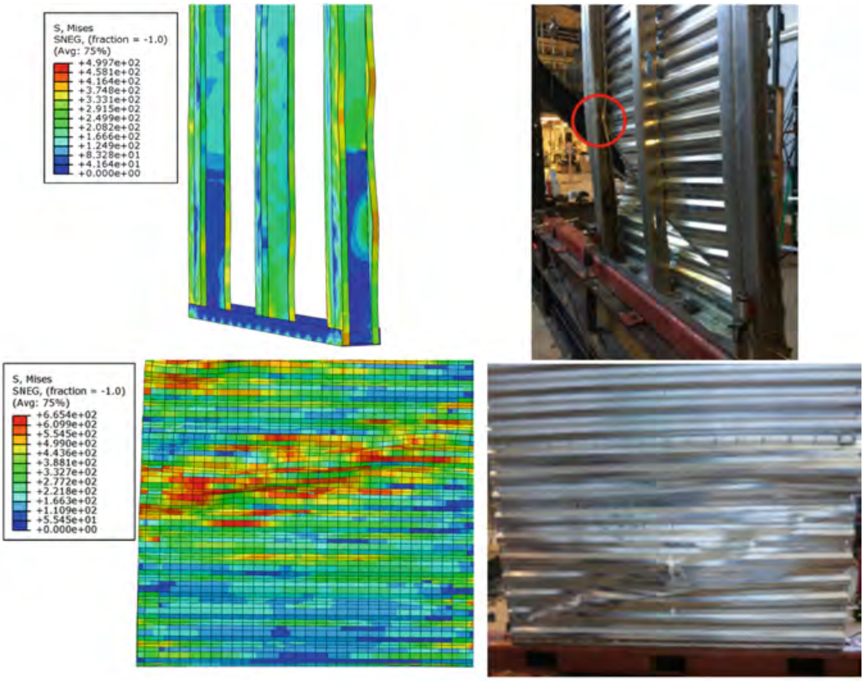


Fig. 4. Comparison of failure modes between numerical model and experimental tests.

3 Parametric Study

The parametric analysis provides an even better insight into the behaviour of DCSWC. Therefore, the parameters that were assumed to influence the behaviour were varied, such as the concrete strength, the thickness of the corrugated sheeting, the diameter of the bolts and the arrangement of the bolts. Table 2 lists all the varied parameters, while Fig. 5 shows the considered cases of bolts arrangement.

Figure 6 shows the numerical load-displacement curves for all models considered in the parametric analysis. Although all models experienced buckling of vertical framing members with the formation of diagonal damage and damage in the slab along the central frame member, differences in the behaviour of the individual models were observed. Therefore, by increasing the strength of the concrete, it was observed that greater shear wall resistance is achieved. However, it can also be seen that the model with lightweight concrete achieves a similar resistance to the model with normal-weight

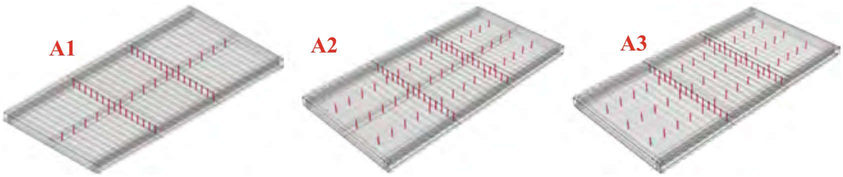


Fig. 5. Arrangement of bolts.

Table 2. Specifications of parameters varied within the parametric study.

Model name [DSWC_xx]	Concrete class	Thickness of corrugated sheathing [mm]	Diameter of bolts	Arrangement of bolts
C20/25	**C20/25**	0.68	M12	A1
C30/37	**C30/37**			
LC20/22	**LC20/22**			
CS068	C20/25	**0.68**	M12	A1
CS10		**1.0**		
CS15		**1.5**		
M10	C20/25	0.68	**M10**	A1
M12			**M12**	
M16			**M16**	
A1	C20/25	0.68	M12	**A1**
A2				**A2**
A3				**A3**

concrete, whereby the weight of the shear wall is significantly reduced. Further detailed examination of the model revealed that the concrete in the model (DCSWC_LC20/22) fractures significantly without forming expected diagonal tension and compression damage as has occurred in the model with normal concrete, as shown in Fig. 7. Changing the thickness of the double-skin corrugated sheeting leads to a slight increase in resistance. Also, according to the shape of the curve, it can be observed that increasing the thickness of the double-skin corrugated sheeting tends to result with a higher yield strength of the shear wall. Furthermore, changing the diameter of the bolts has no significant effect on the behaviour of the shear wall. Also, the arrangement of the bolts (DCSWC_A2) does not contribute to a significant difference in the resistance of the shear wall compared to the base model (DCSWC_A1), while it does contribute to the wall ductility. However, the model with an A3 arrangement of the bolts (DCSWC_A3), which does not include a central frame member, shows a difference in resistance and ductility compared to the base model with a smaller number of bolts. In addition, such a model without a central frame member diagonally damages along the width of the wall. From this, we can conclude that the central frame member contributes significantly to the resistance and ductility of the shear wall and ultimately to the development of diagonal damages in concrete.

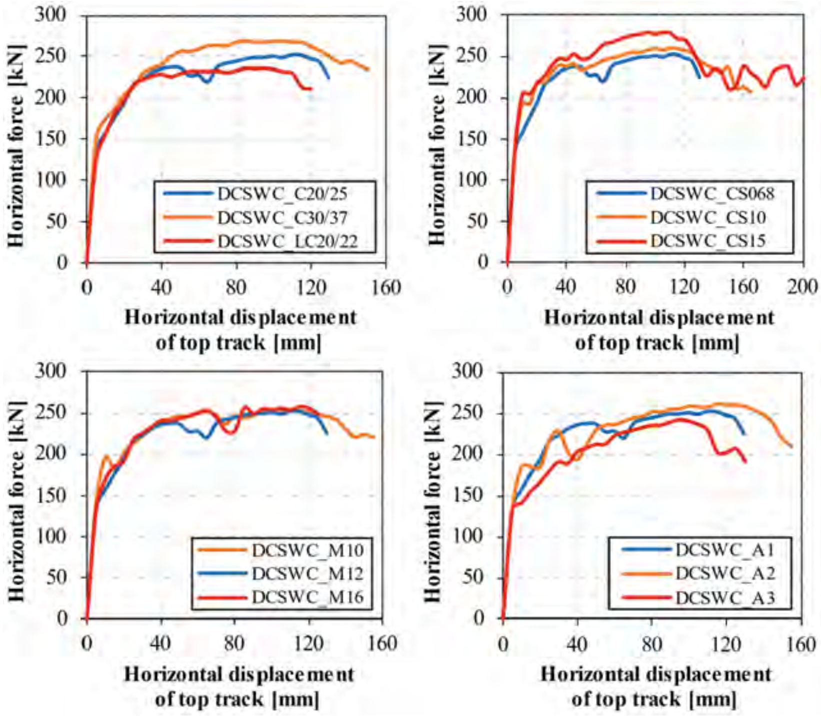
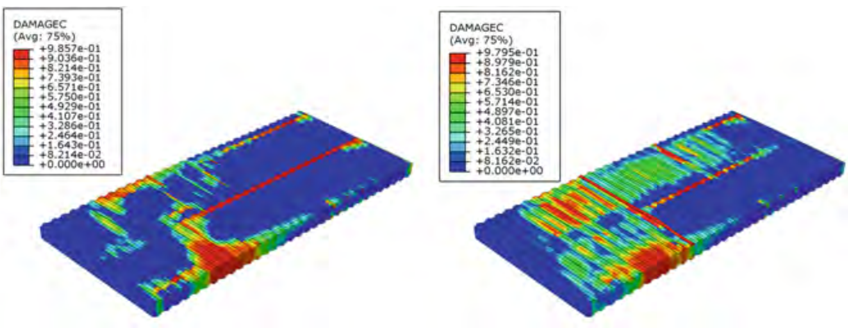


Fig. 6. Load-displacement curves for parametric models.



a. DCSWC_C20/25 b. DCSWC_LC20/22

Fig. 7. Compression damage of concrete slab.

4 Conclusions

In this study, a preliminary numerical analysis of the behaviour of a double-skin CFS shear wall filled with concrete under the influence of a monotonic load was performed. First, the finite element modelling technique for a single-skin CFS corrugated shear wall without a concrete layer was presented. Then, the modelling technique was validated with a reasonable agreement between experimental and numerical results. A parametric analysis was performed to gain knowledge and insight into the influence of individual parameters on the behaviour of the double-skin CFS shear wall filled with concrete. Based on the results of the parametric analysis following conclusions can be provided:

- The change in concrete strength contributes to the increase in shear wall resistance. In addition, when using lightweight concrete, it is possible to achieve similar resistances to normal concrete, while significantly reducing the weight of the system itself.
- Models with lightweight concrete cause more sudden fractures in the concrete and insufficient formation of diagonal damages in the concrete slab.
- Changing the thickness of the corrugated sheeting slightly affects the resistance of the shear wall. In addition, increasing the thickness of the corrugated sheeting tends to result with a higher yield strength of the shear wall.
- The diameter of the bolts that are embedded into the concrete has no significant influence on the behaviour of the shear wall. However, it was found that the arrangement of the bolts as well as the presence of the central frame member can significantly influence the behaviour of the shear wall in terms of resistance and ductility.

This study is an introduction to the research of a new shear wall system that can be used as an innovative bracing system in highly seismic areas. However, further experimental and numerical studies under cyclic loading are required, which will give a better insight into the behaviour of the shear wall. Also, the connection of the CFS shear wall to the steel frame structure needs further research so that the wall can be dismantled after its inelastic deformation and replaced by a new CFS shear wall.

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Comparative Experimental Study on Improving Structural Performance of the Base Upright Profiles of Steel Storage Pallet Racks Under Operational Conditions

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Abstract. In recent decades, economic growth and globalization have spurred increased demand for efficient storage systems, leading to the extensive production of industrial racks from cold-formed steel profiles. Technological advances and research have significantly enhanced the optimization and mechanical efficiency of these profiles. However, older structures often require reassessment and strengthening to meet current and future load-bearing requirements, especially when systems are continuously in use and interventions must be minimized in terms of time and complexity. This paper investigates two strengthening solutions designed to improve the structural performance under various loading conditions, using experimental research to assess and understand the behavior of reinforced profiles. It presents a comparative analysis of the axial compression behavior of the base upright profiles of steel storage racks, each 1 m in length. A specific open cross-section with perforations was utilized, and a total of 13 specimens were tested: 5 unreinforced, 3 with '2L-shaped profiles' for method 1, and 5 with '1C-shaped profile' for method 2. For the strengthened profiles, both methods were secured inside the original profile using M8 bolts. The results demonstrate a 25% improvement in compression resistance capacity for method 2 and 4% for method 1, underscoring the effectiveness of these interventions.

Keywords: Cold-Formed Steel Profiles · Steel Storage Racks · Experimental Research · Strengthening Solutions

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1 Introduction

The economic growth and rapid industrialization of the past decades have led to a larger number of efficient and robust steel pallet rack systems. These structures mainly use cold-formed steel (CFS) profiles due to their high strength-to-weight ratio. At the same time, these structural systems can be customized and are easy to assemble in various configurations. The slenderness and method of cold forming led to inherent vulnerabilities, especially in the uprights at the base of the structures. In addition, the almost complete lack of structural redundancy makes these elements essential for the overall stability and load-bearing capacity of the entire system. There are numerous research studies and publications, especially in recent years [1–3] and a considerable number of design codes [4–7].

Experimental studies on the behavior of cold-formed profiles and finite element numerical analyses have been conducted in various research centers. For example, in the papers [8, 9] the authors proposed an efficient method to increase the resistance capacity of vertical frames under compression using bolts and spacers distributed in intervals along the height. They conducted experimental tests on 81 vertical frames with different thicknesses and heights, and the effect of employing strategies to improve structural performance was examined through failure mechanisms and load-bearing capacity. The study concluded that the effect of section thickness on the performance of vertical elements is considerable and should be investigated through experimental tests. It was also observed that the structural performance of longer strengthened or non-strengthened specimens is not influenced as significantly as shorter specimens. This is mainly because the buckling failure of longer uprights is governed by the flexural and torsional flexural buckling, and strengthening solutions does not necessarily change or control the buckling mode.

In particular, the vulnerability of the base upright profiles has been the focus of recent works such as [10–12], where the failure modes under axial loading were discussed in detail. The paper [12] focused on the experimental investigation of interactive buckling in steel pallet rack compressed members. The study was carried out at the CEMSIG Research Centre of the Politehnica University of Timisoara, where both perforated and non-perforated upright members with two different cross-sections were tested according to the European design code EN15512 for pallet rack systems. The aim was to determine the ultimate strength of the specimens corresponding to local and distortional buckling for critical length equal to the distance between two subsequent nodes of an upright frame. Special attention was paid to the observation of distortional buckling in upright members. It was found that due to varying cross-sectional dimensions, the length between nodes often exceeded the distortional critical length, leading to results that correspond more to the interaction between distortional and global buckling rather than pure distortion. To address this, additional specimens were tested at lengths calibrated for distortional buckling and interactive distortional-overall buckling range.

In a context where there are already stores and warehouses with pallet rack storage systems (as can be seen in Fig. 1) which are nearly 30 years old, built according to the standards available at that time, coupled with the shock from the recent seismic activities in 2023 in the world, there are serious concerns about the current structural behavior and performance of these structures in Romania, especially for those located in strong seismic areas. Additionally, the issue of interventions concerning the possible strengthening of these structures has been considered, particularly the lower segment of the uprights located near the support of the vertical frame. The upgrade of the rack structural system based on evaluation and design checks in most of the cases require strengthening, which must be performed under normal operating conditions, to avoid economic losses caused by suspending the current activity.

Fig. 1. Pallet rack storage system in a typical warehouse in Romania and the dimensions of the vertical upright frame.

This study contributes to the level of knowledge by presenting a comparative experimental analysis of two strengthening solutions for the base upright profiles of steel storage pallet racks, under operational conditions.

2 Experimental Study

2.1 Sections and Materials

Table 1 presents the specimens, together with material description, reinforcement cross-section profiles and the connections used to create the reinforced specimens.

The material used was established by the supplier of the specimens, who was directly interested in this study, because the specified material is used in the production of the rack structures in Romanian market.

The cross-section of the upright profile is presented in Fig. 2a together with a detail of the stiffening, is labelled "R (reference) 85 × 52 p50" and is perforated only on the

Table 1. Specimen and materials description.

Specimen	Description	Material	Reinforcement cross section profile	Connection
(R) 85 × 52 p50	reference profile	S355J2C	NA	NA
(2L) 2L85 × 52 p50	method 1	S355MC	2L 43.5 × 23	M8@300mm
(C) C85 × 52 p50	method 2	S355MC	C 80 × 40	M8@300mm

front side. The thickness of the steel sheet is 2 mm and the material is S355J2C. The side and front views of the profile with perforations are presented in Fig. 2d.

The cross-sections of the reinforcement profiles (see Figs. 2e and 2f) are made of the same materials with the same thickness. The reinforced specimens and their components before the experimental tests are presented in Fig. 3.

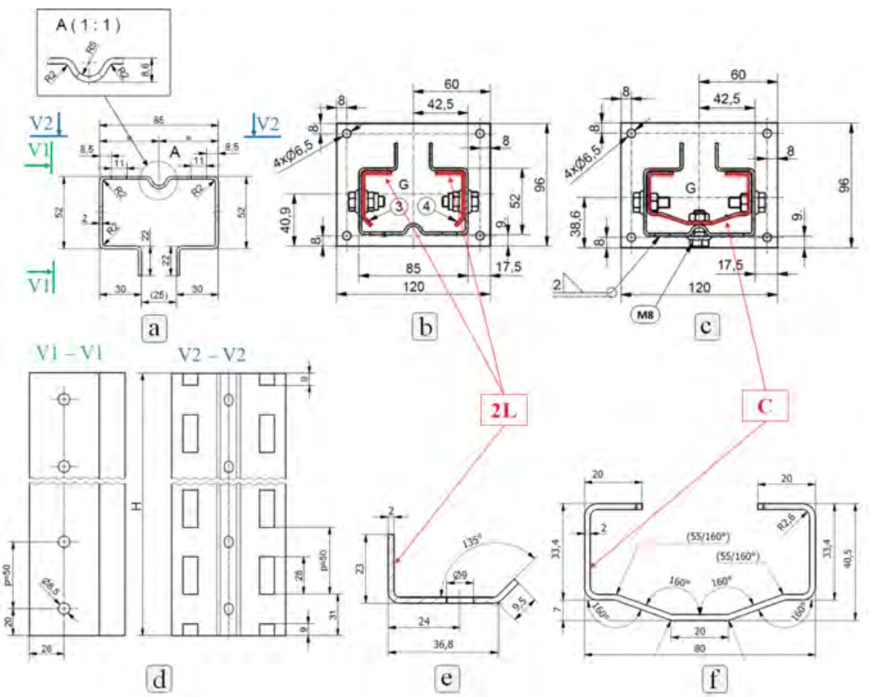

Fig. 2. Cross-section details of the upright profile: (a) basic cross-section without reinforcement, labelled (R) 85 × 52 p50; (b) first reinforcement method, labelled (2L) 2L-85 × 52 p50; (c) second reinforcement method, labelled (C) C-85 × 52 p50; (d) side views V1 and V2 of the profiles; (e) L shaped reinforcement cross-section (method 1); (f) C shaped reinforcement cross-section (method 2).

In the case of the second reinforcement method (C), only three specimens were tested instead of five due to technical conditions regarding the provision of reinforcement profiles. Both strengthening methods used M8 bolts to fix the additional profiles internally to the original. The bolts were spaced at 250 mm. In the case of (C) C85 × 52 p50 profile there were 3 bolts on the same section in comparison with the first reinforcement method (2L) 2L85 × 52 p50 which used only 2 bolts per section. This connection method allowed minimal interruption in the activity of the storage rack system. The aim was to assess the viability and effectiveness of these solutions in enhancing the compression resistance capacity of the profiles, thereby ensuring a safer and more reliable racking system. It is important to note that the cross-sections of the reinforced upright profiles used in this study are non-compact, which plays a significant role in their buckling behavior and overall structural performance under axial loads.

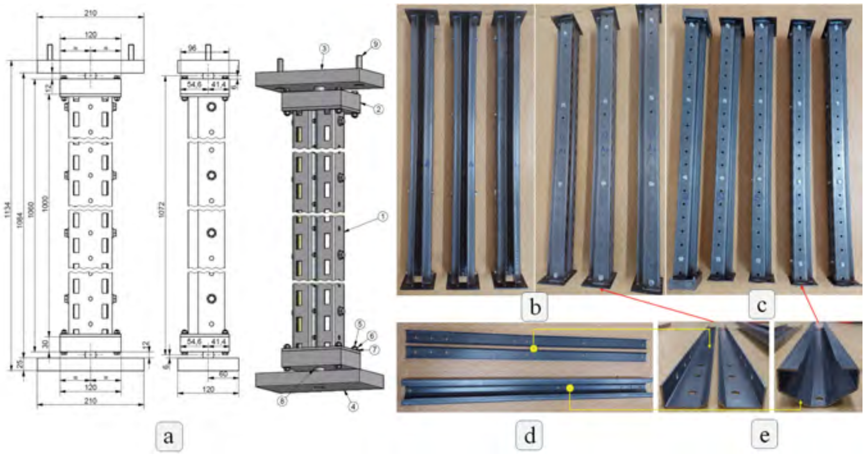

Fig. 3. Assembled upright specimens: (a) 3D view of the (2L) 2L85 × 52 p50 specimen; (b) assembled specimens (2L) 2L85 × 52 p50; (c) assembled specimens (C) C85 × 52 p50 profile; (d) 2L and C shape reinforcement profiles; (e) cross-sectional view of the reinforcement profiles.

2.2 Methodology

The specimens were tested in a universal testing machine with a manual operating system. In accordance with the testing guidelines [4, 13], thick plates fabricated from 30 mm steel sheet featuring a cut-out for the insertion of a 22 mm diameter steel ball were affixed to the ends of the profiles. Corresponding steel plates, identical in thickness and cutout dimensions, were secured onto the testing machine. The placement of the balls coincided with the center of gravity of the net profile cross-section, being a complete hinge capable of transmitting axial compressive loads. A load cell with a maximal operational capacity of 500 kN was fixed at the top part of the machine. Displacement measurements were conducted using two Linear Variable Differential Transducers (LVDT) arranged diagonally to record axial displacements. The loading force was applied monotonically at a rate of 1.5 kN/s until the point of specimen failure. The force and displacement data were systematically captured via the acquisition system and subsequently analyzed to generate the force-displacement curves.

Figures 4 (a-c) present the experimental tests setup for the: (a) non-reinforced specimen, (b) reinforced specimen according to method 1 using 2L-shaped reinforcement profiles and (c) reinforced specimens according to method 2 using a C-shaped reinforcement profile.

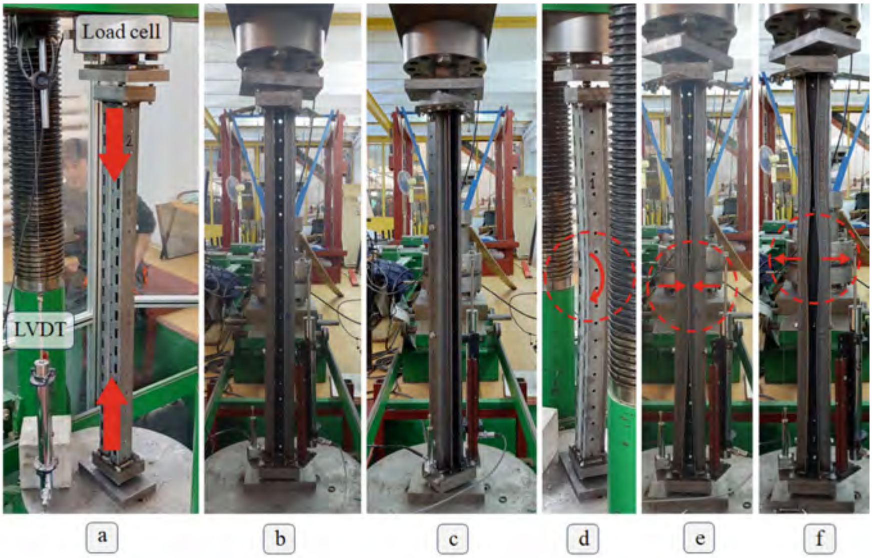

Fig. 4. Experimental tests: (a) non-reinforced specimen setup; (b) specimen setup for method 1 reinforcement with 2L-shaped profiles; (c) specimen setup for method 2 reinforcement with C-shaped reinforcement profile; (d) failure mechanism of the non-reinforced specimen; (e) failure mechanism of the specimens with 2L-shaped reinforcements; (f) failure mechanism of the specimens with C-shaped reinforcement.

3 Results and Discussion

The total number of specimens tested was 13, of which: 5 were non-reinforced, 3 were reinforced with method 1, and 5 with method 2. The failure mechanisms of the tested specimens followed expected patterns. As shown in Fig. 4d, the non-reinforced specimens exhibited flexural buckling at mid-span around the weak axis of the cross-section. The strengthening method 1 led to a distortional buckling failure mode (Fig. 4e). In the case of the reinforced specimens with method 2 (Fig. 4f), the additional stiffness provided by the “C” reinforcement profile slightly changed the overall behavior. Based on the deformation patterns, the failure mode appears to be distortional buckling too, with a shorter wavelength. This failure is characterized by flange deformations occurring along the upright. In the picture of Fig. 4f, we can see that the column produced a three-wave pattern along its length, which indicates a distortional buckling with shorter wavelength as in Fig. 4g. This typically happens when the stress exceeds the critical stress for distortional buckling in these elements, causing them to buckle outwards or inwards.

The test results were recorded in the data files for the loads and displacements in a consistent time interval of 0.2 s. These were processed using the Origin software, where the curves for each tested specimen and the average curve for the set of tested specimens were plotted.

A comparative graph is presented in Fig. 5, which features the three average curves, representing the load-displacement curves for the three sets of recordings.

The graphs present three distinct load-displacement curves for the tested specimens. The unreinforced profile labelled (R) 85 × 52 p50, demonstrates a maximum load capacity (F_m) of 134.40 kN. This value serves as the benchmark for evaluating the effectiveness of the reinforcement methods applied to the other specimens.

The first reinforcement method, marked as (2L) 2L85 × 52 p50, shows an increased maximum load capacity to 138.91 kN, a modest improvement over the non-reinforced profile. This suggests that while the 2L reinforcement provides additional strength, the increase is not as significant as might be expected. The results show that the "2L" reinforcement configuration has a limited impact on the overall load-bearing capacity of the profile, because flange rotational stiffness is not improved effectively by the 2L reinforcement, connected only to the flange of the upright profile.

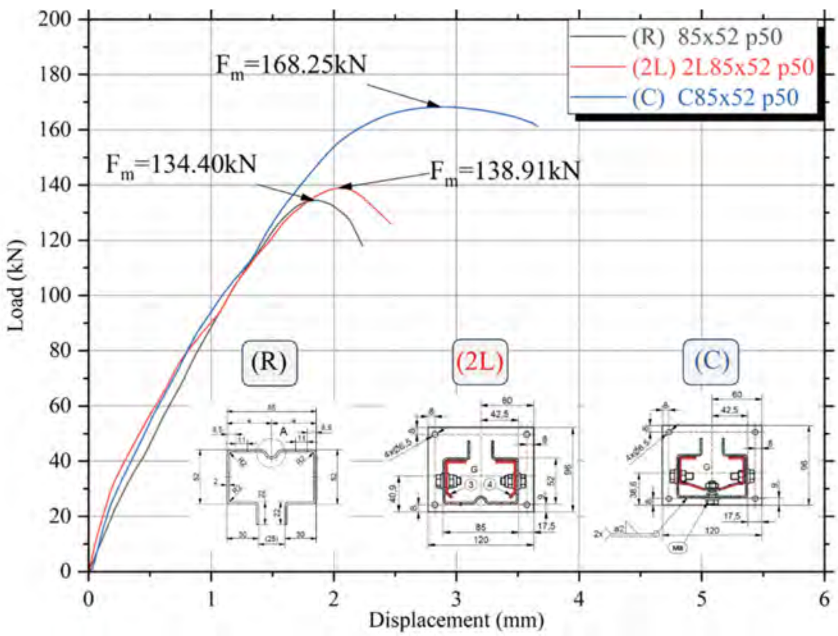

Fig. 5. Comparative load-displacement curves for the reinforced and non-reinforced profiles.

In contrast, the second reinforcement method, using a C80 × 40 profile and labelled as (C), exhibits a significantly higher maximum load capacity of 168.25 kN. This is a considerable enhancement compared to the non-reinforced and 2L reinforced profiles, the reinforcement contributing to the rotational stiffness of the flanges, creating connection to the web of the original profile too. The C-shaped reinforcement contributes not only to the increased load carrying capacity, but also appears to improve the axial deformation capacity of the profile, as evidenced by its ability to support higher loads at increased displacements.

The reinforced specimens (2L and C) show improved deformation capacity compared to the non-reinforced specimen (R), the C-shaped reinforcement (C) exhibiting the highest displacement before reaching the maximum load.

Comparing the reinforcing solutions, it proves to be more effective the one which have impact on the critical length. The 2L reinforcement seems to have no impact on the distortional wavelength (critical length for distortional buckling not influenced by the connecting bolts – Fig. 4e). In contrast, C reinforcement proves to be more effective, the distortional wavelength is formed between the fixing bolts position (critical length for distortional buckling reduced to the distance between connecting bolts – Fig. 4f). The non-compact nature of the cross-sections significantly contributed to the observed failure modes, particularly influencing the buckling behavior and load capacity under axial compression.

4 Conclusions

The investigation presented in this study offers alternative solutions to improve seismic performance by reinforcement of existing steel storage pallet racks, a subject of growing importance in the context of growing needs for warehouses located in seismic areas. The experimental results emphasize the effectiveness of employing reinforcement methods to enhance the structural performance of cold-formed steel profiles commonly used in cold-formed steel storage rack systems.

Through meticulous experimental procedures, the study has shown that the second reinforcement method, employing a C-shaped profile, resulted in a notable 25% improvement in compression resistance capacity, thus significantly bolstering the structural integrity of the profiles. The first reinforcement method, while producing a modest 4% increase, still provided valuable reinforcement, indicating that even minor modifications can contribute to the overall stability and safety of such systems, but probably economically unfeasible.

It was observed that reinforcement method can be more effective, when buckling mode or buckling length is influenced: from flexural buckling (non-reinforced profile) to distortional buckling (2L reinforcement) or one wave (2L reinforcement) to three waves (C reinforcement). The increase in load carrying capacity was especially evident in the second reinforcement method.

The implications of these findings are two-fold. First, they validate the potential for retrofitting existing pallet rack structures to meet more demanding operational and safety standards, particularly in seismic zones. Second, they provide a benchmark for the industry, suggesting that the integration of reinforcement profiles into newly designed structures could be a prudent standard practice, contributing to the increased reliability of storage systems.

This study underscores the need for ongoing research and development in the field of refurbishment of steel structures, particularly in the face of evolving industrial needs and environmental challenges. The results of this research offer a promising direction for future studies and practical applications in the design and enhancement of reinforcing steel storage racks, aiming for an optimal balance between structural performance, economic viability, and increased safety.

The limitations of the study consist of the following aspects:

- Sample size and section diversity: The study used a limited number of samples (13 in total), which may not fully represent the wide range of operational conditions and section configurations found in commercial storage systems. Additionally, only two reinforcement methods were tested, which may not cover all possible reinforcement strategies.
- Scale of specimens: The experiments were carried out on 1 m lengths of upright profiles. This scale may not accurately reflect the behavior of full-size structures under actual loading conditions, especially in varied environmental contexts.
- Material variability: The profiles were made from a specific type of steel (S355J2C and S355MC). The results might differ with other steel grades or materials commonly used in different regions or industries.
- Load application: The loading force was applied monotonically at an approximate rate, which simulates a specific type of loading. Real-world scenarios may involve dynamic or cyclic loading, which could influence the performance of reinforcement methods.

Future research may encompass a broader spectrum of materials to assess the versatility of reinforcement methods in various steel sections, steel grades and alternative materials. It would be beneficial to extend the investigation to dynamic and cyclic load tests to better simulate seismic events and more realistic operational conditions. Furthermore, experimental validation through full-scale structural testing could offer a more in-depth understanding of the performance of the reinforcement methods in real-world scenarios.

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Performance Comparison of Different Vibration Control Strategies

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Abstract. Structural engineers are always struggling with the unpredictable complexities of the extreme vibration due to natural or human induced loads. It is not possible to eliminate the vibration from structures entirely what so ever. Therefore, in order to keep the structures safe and healthy, the vibration needs to be mitigated and that can be done by adopting passive, active or semi-active type control systems. Those aforementioned technologies come with a price, hence, it is not so straightforward to decide which technology should be adopted. The passive vibration systems (e.g. tuned mass damper, base-isolator) can be found both in many old and new structures due to their feasibility and simplicity. On the other hand, many modern structures are adopting active and semi-active control systems (e.g. dampers) as an alternative to achieve better control on structure. Both the active and semi-active control systems are more expensive than passive control systems but they offer better control on structures. In order to understand the discussed issue, herein, a comparative study has been performed to evaluated their performances. A detail comparison among passive, active and semi-active control alternatives have been conducted. The outcome shows that the passive control systems can be suitable where deformations are and the other alternatives would be beneficial where large deformations are expected.

Keywords: Structural Engineering · Dynamics · Vibration Mitigation · Passive Control · Dampers

1 Introduction

Vibration induced problems in the area of structural engineering is quite old and well-known issue but still require further attention due to the complexity of the matter. There are many vibration reduction technologies are available in the real-life applications [1–9]. However, even among those alternatives there is none neither flawless nor foolproof. As a result, the scope is still open for further development and update of vibration control tools and technologies. Among available vibration mitigation strategies, they broadly can be separated into three main categories, such as; (i) passive [8], (ii) active [10], and (iii) semi-active [11]. The working principles of those technologies are quite different from one to other. However, regardless the working mechanism the main goal remains same

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that is the vibration reduction. Based on their mechanism and efficacy, the feasibility is a point that needs to be taken care of [12]. In this regard, the passive strategy might be the cheapest solution in comparison to its alternatives. Additionally, the aforementioned systems do not require any external energy supply into it during the operation. Hence, the application of passive system is quite easy to adopt it. Nevertheless, the performance in terms of vibration reduction of the passive systems might not be the best choice in contrast to active or semi-active systems.

The active and semi-active systems require the energy/power supply during operation. Therefore, it might be a serious problem when an extreme event happens such as earthquake or tsunami. However, in case of aforementioned situation it might an option have a system that is operable during an extreme event without external power supply. For the early mentioned reason, the semi-active or hybrid type systems might be beneficial as they can be operated with and without external power supply. In the real-life applications almost, all of those technologies can be found for various purpose. The passive systems have been adopted in many structures for vibration mitigation such as; offshore structure [13], tall buildings [14], bridge [15]. Additionally, many research can be found that are conducted to update the performance by developing new devices such as a hybrid type passive system for multi-storied building [16], a novel translational tuned mass damper [17], elastomeric bearing [15].

The active and semi-active systems have employed in many structures, for instance, adaptive semi-active control for suspension systems [11], energy-based active control for tensegrity structures [18]. A validation of novel semi-active control scheme has been performed in [19], and reported that system identification and vibration control possible via the use of the unscented Kalman filter. Further, an energy-based control for swinging pendulums have been reported in [20], simultaneous control and monitoring via adaptive control in [21], intelligent control [4].

It is clear from the above discussion that to understand which vibration mechanism works better for what application is quite complicated. Hence, this study has focused to investigate the inter-comparison to understand main three categories of vibration strategies. To achieve the goal of the study, a 3-toried dynamical system is considered and all three control strategies have been implemented. The outcome of the study has been accommodated in the later section of this paper. The rest of the paper contains problems statement, results and discussion and finally, a summary of the study.

2 Problem Statement

The simplified formulation for the modeling of any dynamical problems are widely adopted instead of solving individual equation of motion. Therefore, in this study, the simulations are performed by adopting simplified formulation of structural dynamics so-called the lumped-mass model. In order to solve the dynamical system using the concept of the lumped-mass model, the equation of motion needs to be formulated. The early mentioned equation contains all the necessary information of the dynamical systems.

Herein, the studied 3-degree-of-freedom (DOF) system has been described as,

$$M_{3\times 3}\begin{Bmatrix}\ddot{x}_1\\ \ddot{x}_2\\ \ddot{x}_3\end{Bmatrix}(t)+C_{3\times 3}\begin{Bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\end{Bmatrix}(t)+K_{3\times 3}\begin{Bmatrix}x_1\\ x_2\\ x_3\end{Bmatrix}(t)=\beta p(t) \tag{1}$$

where the mass matrix is given by $M_{3\times 3}=\begin{bmatrix}m_1 & 0 & 0\\ 0 & m_2 & 0\\ 0 & 0 & m_3\end{bmatrix}$, while the damping matrix is $C_{3\times 3}=\begin{bmatrix}c_1+c_2 & -c_2 & 0\\ -c_2 & c_2+c_3 & -c_3\\ 0 & -c_3 & c_3\end{bmatrix}$, and the stiffness matrix is $K_{3\times 3}=\begin{bmatrix}k_1+k_2 & -k_2 & 0\\ -k_2 & k_2+k_3 & -k_3\\ 0 & -k_3 & k_3\end{bmatrix}$, t is the time vector, x is the displacement, $\dot{x}$ means the velocity, $\ddot{x}$ is the acceleration, β is the control vector that control the location of the applied load, p is the external loads.

Later, the equation motion has been transformed into a more compact formulation known as the state space formulation. The state space formulation consists of two main equations (i) system/process equation, and (ii) observation/measurement equation. Briefly, those two equations of state space formulation are given by,

$$\dot{X}(\mathrm{t})=AX(t)+BU(t) \text{ and } Y(t)=CX(t)+DU(t) \tag{2}$$

where A is the system matrix that contains mass, stiffness and damping information of the system, B is input control matrix, C is the output matrix, D is the feedthrough matrix, Y reprents the output vector, X is the state vector.

The comparison of the different control strategies have been performed by considering a three storied structure. The performances are evaluated for both uncontrolled and controlled structures. For the controlled structures the control systems are assumed be laced at the ground floor. The passive control system is given by the simplest form that is given by Eq. (3). It can be found that in the early mentioned equation that only a stiffness component is needed to represent a passive control device. Usually, the passive system is assumed to provide a linear control force that is controlled by the define stiffness of the device.

$$f_{pa}=k_{pa}x \tag{3}$$

In order estimate the control force for the active and semi-active control systems the control forces are defined as shown via Eqs. (5) and (6), respectively. It needs to be mentioned that depending on the choice of the control algorithm (e.g. full-state feedback or partial feedback) all floors displacement and velocity might be essential to calculate the desired control force. Herein is both the active and semi-active full state feedback type control law has been adopted namely the linear-quadratic-regulator (LQR). In other words, the adopted control algorithm required all floors displacements and velocities. The LQR control algorithm is widely used in the real-life applications and the detail can be found in many existing literatures. Briefly, the main equation that minimizes the cost function (J) and thereby optimized the controller performance. The cost function (J) is given as,

$$J = \sum_{0}^{N} \left(X^T Q X + U^T R U \right) and U = \left[-k_{ac}^{d} - k_{ac}^{v} \right] X \tag{4}$$

$$f_{ac} = \left[-k_{ac}^{d} - k_{ac}^{v} \right] \begin{bmatrix} x \\ \dot{x} \end{bmatrix} \tag{5}$$

$$f_{sac} = \left[-k_{sac}^{d} - k_{sac}^{v} \right] \begin{bmatrix} x \\ \dot{x} \end{bmatrix} \tag{6}$$

where the f_{ac} represents the active control force, f_{sac} is the semi-active control force, x and $\dot{x}$ are the displacement and velocity of the system. It is not necessary that ones have to use full-state feedback type control algorithm, depending on the individual problem type he/she may select the partial state feedback type algorithms. Typically, both the active and semi-active control systems are nonlinear and quite complex to model. However, it is assumed that the semi-active control strategies may ignore unwanted active components (see Fig. 6c), if that's not the case then it would behave as active control system. Hence the employed control algorithm needs to be efficient enough to estimate the representative behavior correctly.

3 Results and Discussion

This study investigates the performances of the vibration reduction strategies. To do so, a 3-DOFs is considered and three approaches (i) passive, (ii) active, (iii) semi-active, have been implemented. The simulations are performed for 10 seconds with a sampling frequency of 1000 Hz. The floor masses are assumed to be around 72 Kg while the floor stiffnesses are considered to be around 10000 kN/m. The damping matrix is estimated based on the mass and stiffness properties.

As a first step, all of the floor's displacement have been evaluated and the uncontrolled time-history response has been compared with controlled time-history data. The first, second, and third floors displacement time-histories have been depicted in Fig. 1, 2 and 3, respectively. The uncontrolled displacement data is given by the red line, while the passive controlled case by the black line, magenta line indicates the active controlled case and the green line represents the semi-active controlled case. It can be found in those aforementioned figures that all of the controlled strategies can be beneficial than without having any control. However, it is also noticeable that both the active and semi-active cases may perform better than passive system.

It is necessary to mention that the performance of any control strategy may vary significantly depending on how well-tuned or optimized. The tuning process may play a crucial role in case of active and semi-active control than passive. It is due the complex phenomenon of the active and semi-active control schemes. In other words, tuning process for passive control systems is quite straightforward as there are only two parameters e.g. mass ratio and stiffness.

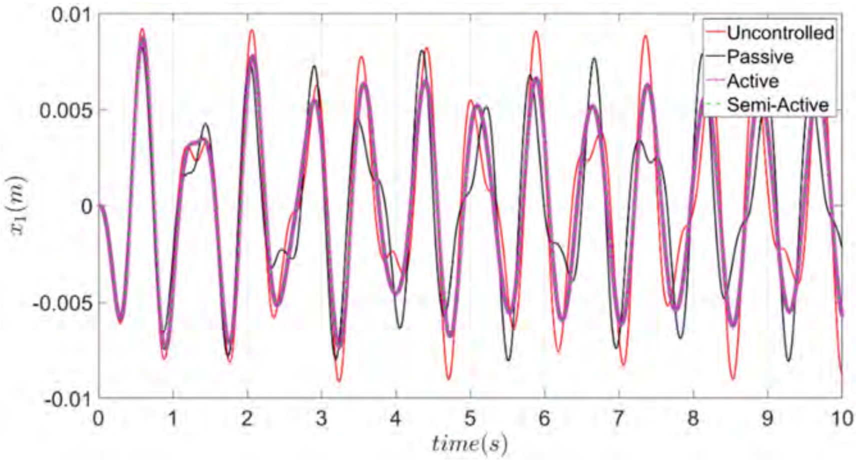

Fig. 1. The comparison of 1st floor uncontrolled and controlled displacements.

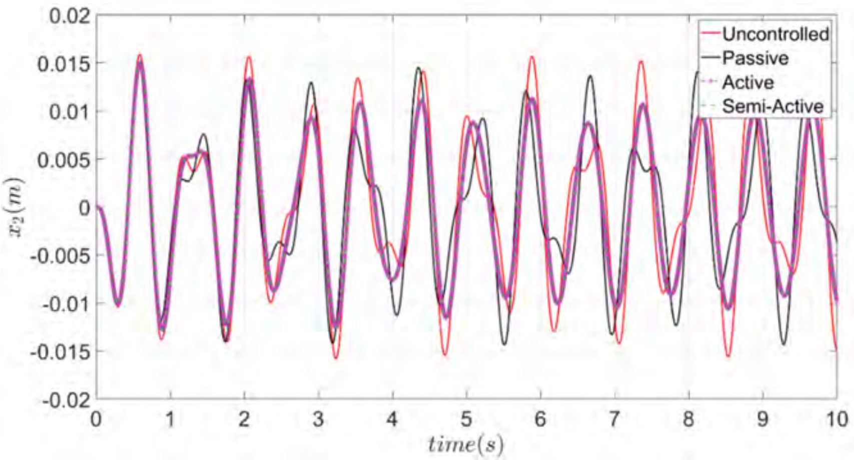

Fig. 2. The comparison of 2nd floor uncontrolled and controlled displacements.

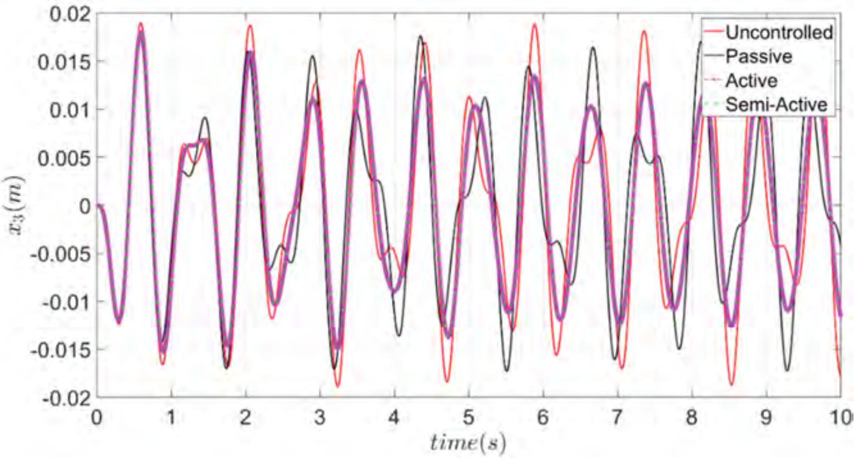

Fig. 3. The comparison of 3rd floor uncontrolled and controlled displacements.

In addition to displacements time-histories, the 3rd floor's velocities (see Fig. 4) and accelerations (see Fig. 5) are also compared. In those figures, it is also visible that the implemented control strategies worked quite effectively.

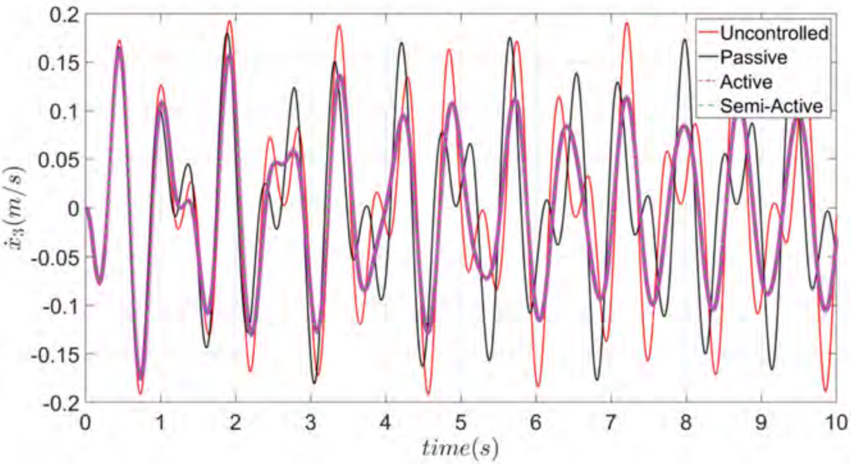

Fig. 4. The comparison of 3rd floor uncontrolled and controlled velocities.

In order to understand that the applied control strategies work, a confirmation of control force versus displacement plot of each control approach has been provided in Fig. 6. The early mentioned figure confirms that the passive (see Fig. 6a), active (see Fig. 6b), and semi-active control strategies (see Fig. 6c) work quite well.

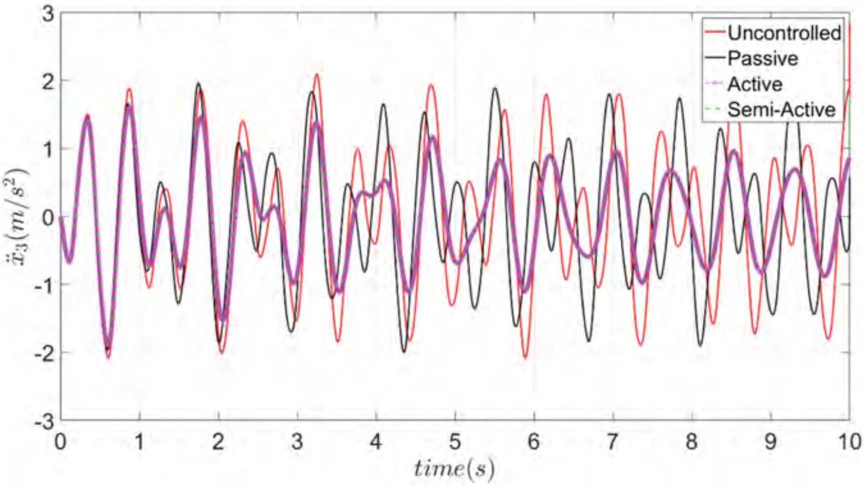

Fig. 5. The comparison of 3rd floor uncontrolled and controlled accelerations.

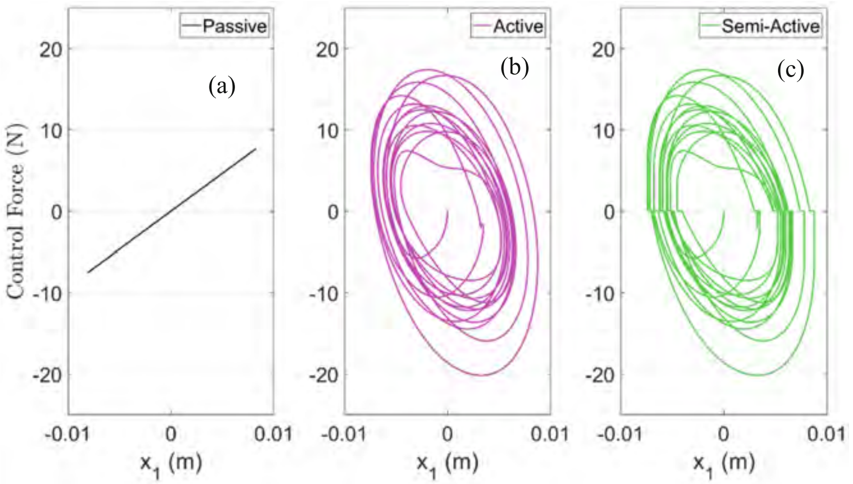

Fig. 6. Overview and confirmation of the implemented control strategies.

To be more precise, ones may easily see that the left sub-figure shows a clear elastic force that was applied by the passive system. Whereas, the middle and the right sub-figures show a complex hysteretic behavior that is what usually expected from any smart control strategy. However, there is a little difference between the middle and the right sub figures, on right sub-figure (semi-active) case note the x-axis because that confirms that this strategy is not same as active control case.

4 Conclusions

This work investigates the performances of different vibration control strategies numerically. To do this end, a 3-DOF system has been adopted and three control concepts have been implemented. The performance of any vibration scheme would come with some drawbacks hence serious assessment is essential by the designers. For instance, herein, it has been observed that the passive mitigation technology may not be suitable for extreme excitations. While the active or semi-active scheme might be beneficial but that would cost more than the passive system. However, considering all limitations (e.g. energy consumption) active and semi-active technologies would be better where extreme level of vibration is expected due to their inherent mechanism that helps to reduce extreme vibration. The authors believe that further study is necessary to enhance the performance as well as the control strategies need to be adopted in more complex structural systems.

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Exploratory Research on the Thermal Properties of Wood in Real Fire Conditions

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Abstract. As construction material, wood represents a response to concerns over the environmental impact caused by steel and concrete. A good performance of timber structural members must be demonstrated in fire. To perform numerical simulations of timber structures under elevated temperatures, EN1995-1-2 provides effective thermal properties of wood for computing the temperature distribution. These properties have been determined considering the standard time-temperature curve. The aim of the exploratory research is to verify to what extent these properties may be considered also for natural fires, by adapting the real exposure conditions within the numerical simulations. In the tests performed at the University of Liège, timber samples were subjected on one side to heat fluxes of different intensities, including decreasing phases. Time-temperature curves inside the samples were recorded by thermo-couples inserted at different distances from the exposed side. Using SAFIR software, dedicated to the analysis of structures under elevated temperatures, the temperature distribution within the samples was calculated considering thermal properties provided by EN1995-1-2. The comparison with the experimental results emphasized that the correspondence is not satisfactory for all cases.

Keywords: wood · natural fire · thermal properties · temperature measurement · numerical modeling

1 Introduction

According to EN1995-1-2:2004 [1] and the revised version prEN 1995-1-2:2025 [2], if advanced design methods are considered for the assessment of the fire resistance of timber members, the thermal response model shall consider the temperature dependent thermal properties of the wood: thermal conductivity, specific heat, and density ratio. Both documents offer effective values of these thermal properties for softwood, as a function of temperature.

The evolution of these properties with temperature was initially determined by [3] for application to standard fire scenarios and should only be used when the conventional heat transfer is applied, that is when mass transport is not explicitly considered [4].

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These are effective values rather than physically measured values, taking into account effects which are not explicitly considered in the thermal analysis, such as increased heat transfer due to shrinkage cracks in the charcoal [1, 2].

Indeed, in a fire situation, while for construction materials as steel and concrete the heat primarily propagates through conduction, the heat propagation within wood members is also influenced by radiation and convection, considering the specific phenomena (e.g. pyrolysis gases, vapor, fissures in charcoal).

Considering that the charring rate of wood varies during a real fire, and this strongly influences the effective thermal properties, the evolution of the thermal conductivity, specific heat and density ratio specified in [1, 2] should not be applied to natural fire scenarios. The restriction to standard fire scenarios is motivated in [4], by means of six fire tests of timber slabs exposed to natural fires.

However, within a numerical thermal analysis, apart from the thermal properties of the material itself, in case of a natural fire there are some other parameters linked to the real exposure conditions, which shall be considered accordingly. The purpose of the exploratory research is to verify if the effective thermal properties of wood given by [1, 2] may be nevertheless considered for natural fire scenarios, even with certain limitations, if the real exposure conditions are properly considered within the numerical analysis.

A series of experiments using an apparatus recently developed at the "Laboratoire d'essai au feu" of the University of Liège were performed, aimed to identify the discrepancies between the real temperature evolution inside of a timber specimen subjected to different heat fluxes and the results of the numerical thermal analysis provided by SAFIR [5], using the effective thermal properties proposed in EN1995-1-2.

2 Experimental Setup

The **s**amples for the experimental work were considered from three beams (Fig. 1), of dried and planed spruce ("Picea abies"), which is classified as softwood. The beams were sectioned off in 250 × 220 × 80 mm test samples. A maximum value for the humidity of 13.4% was experimentally determined for the samples.

The device used as heat source was the experimental apparatus designed at the "Laboratoire d'essai au feu" of the University of Liège, which consists of ten ceramic heating pads divided into five heating zones, as shown in Fig. 2. A full description of the apparatus functionality and of the calibration process can be found in [6].

To produce accurate heating conditions for fire testing, two parameters can be controlled: the distance between the heating pads and the specimen, and the temperature of the heating pads.

The test set-up allows for easy adjustment of the distance between the pads and the specimen. This facilitates the achievement of well-defined heat fluxes at the exposed surface of the samples, ranging from 25–50 kW/m^2. The threshold for self-igniting and maintaining burning during the whole length of the exposure was at a heat flux of about 50 kW/m^2. At lower heat fluxes, the sample would ignite only with a pilot flame.

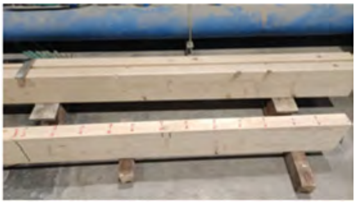


Fig. 1. Beams used for tests.

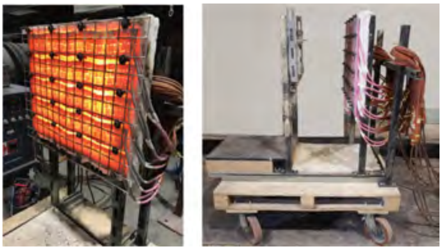


Fig. 2. Heat source.

For distances between the specimen and the heating pads no larger than 300 mm, the view factor can be considered 1. The incident radiant heat flux was determined experimentally, and for the distance of 300mm between the heating pads and timber sample, it was homogeneously distributed over the exposed surface. Therefore, this distance was considered for all tests. In these conditions, for a temperature of the heating pads of 900 °C, the flux received by the specimen was 25 kW/m^2.

To expose the test specimen to a constant heat flux from the beginning and to avoid an excessively long heating phase, a heat barrier was placed between the specimen and the heating pads (a fire-resistant gypsum board). Once the target temperature was reached and maintained, the heat barrier was removed.

The temperatures inside the timber samples were measured using thermocouples (TC), into previously drilled holes. Two directions were tested:

- holes parallel to the grain of the timber sample, parallel to the heat flux (Fig. 3a);
- holes perpendicular to the grain of the timber sample, perpendicular to the heat flux (Fig. 3b).

The holes parallel to the heat flux are more difficult to execute. Due to the geometry of the sample, these holes must go much deeper in the sample, and given that their diameter is 3 mm, the accuracy may be compromised. Before drilling holes in the test sample, some test drills were conducted to determine how accurately the holes could be executed. After drilling five holes at a spacing of 10 mm, with the timber sample properly secured in the drill machine, the timber sample was cut perpendicular to the holes, into 20 mm thick pieces. The maximum measured deviation of the holes was less than 1 mm.

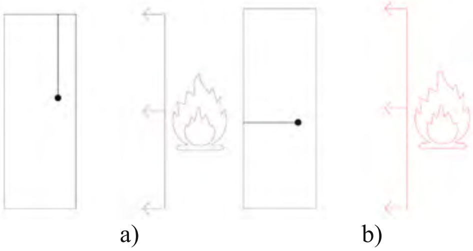


Fig. 3. Direction of thermocouple holes.

Some preliminary tests emphasized that the TC's fixed in drill holes executed parallel to the heat flux recorded higher temperatures than the ones fixed in drill holes executed perpendicular to the heat flux (Fig. 4). Therefore, for all further tests, the TC's were placed considering holes executed parallel to the heat flux. This is in agreement with literature and guidance documents [7, 8], which recommend installing thermocouples parallel to isotherms, to limit the temperature measurement errors in low conductive materials, such as wood.

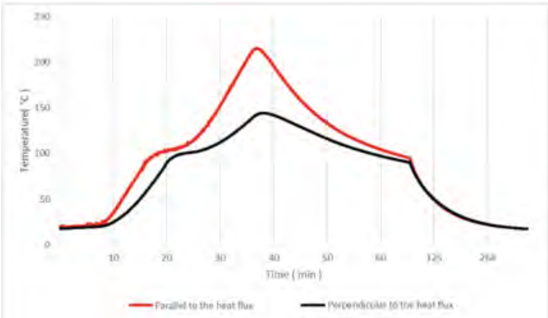


Fig. 4. Comparison between the temperatures recorded in holes parallel and perpendicular to the heat flux.

Two types of TC's were considered: type K sheathed and type K wire unsheathed. The two types demonstrated a very close thermal response, the observed difference being that sheathed wire TC's are more prone to noise during measurements. It must be mentioned that [8] also concluded that the use of sheathed TC's cannot be recommended for absolute temperature measurements within low conductive materials such as timber.

3 Numerical Simulations

A thermal analysis of the tested specimens was conducted using SAFIR software [5]. The net heat flux absorbed by the specimen at the exposed surface Q_{net}, considering the convective and radiative losses is calculated according to Eq. (1):

$$Q_{net} = \alpha \cdot Q_{int} - \alpha_c \cdot (T_S - T_G) - \sigma \cdot \varepsilon \cdot \left(T_S^4 - T_G^4\right) \tag{1}$$

in which:

- α is the absorptivity of the timber equal to 0.8;
- Q_{int} is the incident heat flux;
- α_c is the coefficient of heat transfer by convection;
- T_S is the surface temperature;
- T_G is the gas temperature;
- σ is the Stefan–Boltzmann constant equal to 5.67E−08 $W/m^2 \cdot K$;
- ε is the surface emissivity of the member equal to 0.8.

The value of the incident radiant heat flux Q_{int} was determined experimentally. In the numerical model, the surface temperature was automatically computed in the software) and the gas temperature T_G is equal to 20 °C.

In a first step, both EN 1995-1-2:2004 [1] and prEN1995-1-2:2025 [2] material thermal properties were considered in SAFIR. There are no differences between the two versions of the Eurocode for the values of thermal conductivity and specific heat. For the density ratio, the revised version [2] offers values which are no longer dependent on the moisture content until 99 °C. The values of the density ratio were calibrated with an initial moisture content for service class 2.

To illustrate the difference between the two versions of the Eurocode, Fig. 5 depicts a comparison of the evolution of density ratios, assuming a moisture content of 20%. The revised version [2] leads to a more pronounced decline in the density ratio, starting with the temperature of 121 °C, compared to the current version [1].

For the numerical thermal analysis, the following parameters were defined:

- coefficient of heat transfer by convection for the standard fire curve on the heated surface $\alpha_c = 25$ W/m^2K;
- coefficient of heat transfer by convection on the unheated surface $\alpha_c = 4$ W/m^2K;
- surface emissivity of the member $\varepsilon = 0.8$.

Figure 6 shows the comparison between the experimental and numerical results, at the level of the TC's placed at 30mm depth from the exposed side, for 30 and 60 min of exposure. It may be observed that prEN1995-1-2:2025 [2] thermal properties lead to a slightly better evolution of the temperature – time curves, with a maximum temperature discrepancy of about 20% for 30 min of exposure. For further numerical simulations, the revised thermal properties of prEN1995-1-2 were considered.

Compartment fires occur within enclosed spaces where ventilation is limited. In the present study, the experimental samples are exposed to unrestricted air supply from all sides, allowing for efficient combustion and ventilation. Therefore, the coefficients of heat transfer by convection on both exposed and unexposed sides should be modified accordingly.

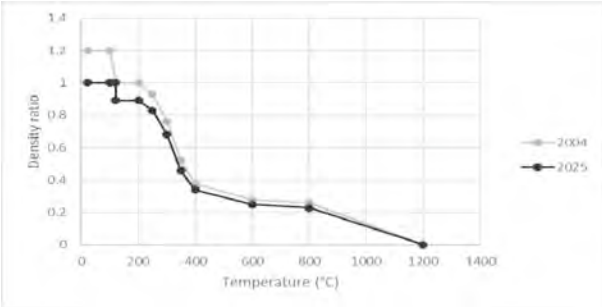
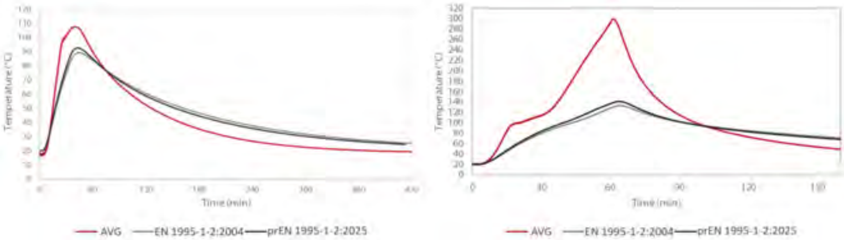


Fig. 5. Comparison of density ratio as a function of temperature for timber with an initial moisture $\omega = 20\%$.



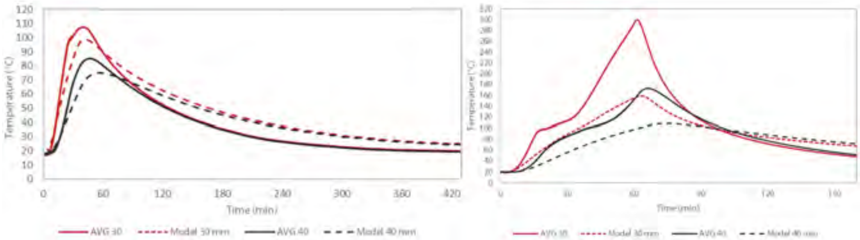
a) b)

Fig. 6. Evolution of temperature after a) 30 min and b) 60 min of exposure.

To account for exposure conditions closer to reality, the coefficient of heat transfer by convection on the exposed surface was modified to 10 W/m^2K. The coefficient of heat transfer by convection on the unheated surface, initially set at 4 W/m^2K to account for natural convection, has been adjusted to 25 W/m^2K, to simulate forced convection.

Figure 7 shows the comparison of the evolution of the temperatures between the experimental and numerical results, at the level of the thermocouples placed at 30 mm and 40 mm depth from the exposed side, for 30 and 60 min of exposure, considering the above modifications. It may be observed that the numerical models incorporating the modifications exhibit a slightly faster cooling rate after reaching the peak temperatures, which are closer to the experimental values.

Thermal camera observations (Fig. 8) revealed that the gas temperature T_G in front of the exposed surface exceeds up to a maximum of 250 °C the temperature considered for the heat exchange with the ambient air in the numerical models (20 °C). A new function representing the ambient air in the vicinity of the exposed surface was then considered in SAFIR, derived from measurements obtained through the thermal camera. On the unexposed surface, the temperature function remains at the ambient air temperature of 20 °C.



a) b)

Fig. 7. Evolution of temperature with modified coefficients of heat transfer by convection after a) 30 min and b) 60 min of exposure.

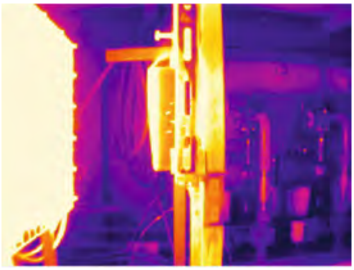
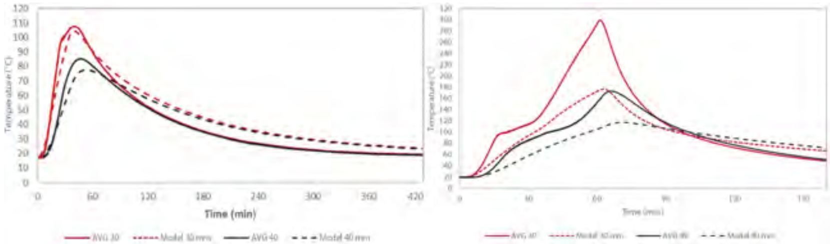


Fig. 8. Side view of the sample during captured by the thermal camera.

As Fig. 9a demonstrates, for 30 min of exposure, a better fit between the numerical and experimental peak temperatures is obtained by incorporating the new function for ambient air. A better fit is also obtained for the cooling rate, for a period of about 30 min after reaching the maximum temperature. Afterwards, the temperatures decrease at a slower rate in the numerical simulations, which means that the numerical model offers conservative temperature values for the cooling phase.

For 60 min of exposure (Fig. 9b), the temperatures obtained from the tests are still significantly higher than those of the numerical models. The numerical simulations fail to reproduce in a satisfactory manner the experimental temperature evolution for exposures longer than 30 min.



a) b)

Fig. 9. Evolution of temperature with modified coefficients of heat transfer by convection and revised gas temperature after a) 30 min and b) 60 min of exposure.

4 Conclusions

Timber is a heterogeneous material and during a fire exposure its thermal properties vary across the cross-section, being strongly affected by the charring rate. In the numerical analysis, if the initial geometry is assumed throughout the entire duration of fire exposure, the time-dependent changes in the effective thermal properties of wood, provided by EN1995-1-2, can be considered for standard fire exposure.

The exploratory research indicates that it may be possible to consider these effective thermal properties also for natural fires, with satisfactory results in case of short exposure times, up to 30 min, if the parameters linked to the real exposure conditions are properly considered.

The results are encouraging for starting an extended experimental and numerical study, to propose modified effective thermal properties for wood, adapted to different natural fire exposure conditions.

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Assessment of Existing Structures for Elongation of the Buildings Lifecycle Based on Ukrainian Experience and Codes

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Abstract. One of the effective ways to increase the efficiency of the circular economy is the reuse of existing structures and parts of buildings or extending the life cycle of existing buildings. Assessing the technical condition of existing systems is the basis for reliable and safe operation, both of structures and buildings as a whole. The paper analyses the history and development of Ukrainian standards (codes). It compares methods for evaluating the technical condition of existing structures presented in Ukrainian standards with those shown in the international standard for assessing existing members. Over the past 30 years, Ukraine has actively developed methods for assessing the technical condition of existing steel, reinforced concrete and composite structures. The basis of the results of the analyzed works is theoretical, experimental, and full-scale studies of existing structures. Much work is devoted to assessing the reliability of existing and damaged building structures. Methods of reliability theory have been applied to evaluate enclosure structures, for which a new term - thermal reliability of enclosure structures - has been introduced. Based on the analysis of codes and research, recommendations have been prepared for implementing sustainable practices into European standards.

Keywords: Buildings Lifecycle · Existing Structures · Assessment · Actual Condition · Reliability · Standards · Regulations

1 Development and Structure of Regulatory Framework for Inspection of Existing Constructions

The modern history of the regulatory construction framework in Ukraine began in 1991 with the attainment of independence. For a long period in Ukraine, Soviet construction norms and standards were in effect. Currently, Ukraine distinguishes between documents of two levels - state construction norms (DBN) and national standards (DSTU).

It is worth noting that as of 1991, the system of Soviet construction norms lacked documents on inspecting the technical condition of buildings and structures. Various industry-specific documents were used for this purpose. For instance, VSN 57-88 [1] was

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used to inspect residential buildings and different documents were used for industrial buildings. Inspection of steel structures of industrial buildings could be carried out according to ORD 00 000 89 [2] or the Guide for the Design of Strengthening of Steel Structures [3] based on the applicable norm at that time. Similar recommendations for the inspection and strengthening of reinforced concrete structures can be found in [4], and this is a partial list of various recommended, methodological, and auxiliary documents. In the list of recommended sources for [5], 34 documents issued in the 1970s-80s dedicated to the issues of technical inspection, assessment of the technical condition, and strengthening of damaged structures could be found. Logically, many guides led to different groups of engineers using different documents, resulting in works on assessing the technical condition of buildings and structures by professionals working within the same city being carried out in different ways, yielding different results.

In 1995, Ukraine introduced DBN 362-92, "Assessment of the Technical Condition of Steel Structures of Industrial Buildings and Structures in Operation" [6] - the first state construction normative document developed by a group of scientists under the leadership of A. Perelmuter. Although it was a progressive document, it included parts from the abovementioned documents [2, 3]. Its main advantage was the clear and logical structure – the document contained information on the procedure for conducting technical inspections and assessing the technical condition by various methods: analytical, which is based on tables of typical defects and damages, and recommendations for determining the technical condition based on the conducted inspection. The most exciting provisions were recommendations for refining steel properties in structures and refining the actual loads and impacts. One of the weaknesses of this norm was that, despite its status, it remained an industry-specific document, as it was intended only for the assessment of steel frames of industrial structures. Another weakness was that the classification of technical conditions differed in names from other documents, including those for inspecting industrial buildings and structures. In 1997, the Cabinet of Ministers of Ukraine adopted a resolution requiring all industrial enterprises to certify buildings and structures. Each building was supposed to have a passport with drawings, a description of structures, loads that these structures can withstand, established technical conditions, and recommendations for further safe operation. The passport was compiled based on a technical inspection. To determine the technical condition (there were a total of 4 – from normal to emergency), a document [7] was created, a collection of various legislative acts, including those regulating the technical condition of buildings. Unlike [6], the classification of the technical condition was envisaged only based on visual parameters. At the same time, this document introduced the calculation of the term of the next planned inspection, which was based on the term of the previous one and coefficients that depended on the technical condition of the structure and the aggressiveness of the surrounding environment.

The schedule for planned inspections of buildings (structures) was recommended to be determined based on the safety coefficient using the formula:

$$T = T_b \cdot K_b, \textit{years} \tag{1}$$

where T_b is the term until the first planned inspection for buildings (structures) operating under average conditions for a given industry.

The safety level of buildings (structures) is assessed by the safety coefficient K_b, which is the product of three coefficients: the purpose reliability coefficient (Y_n), the coefficient characterizing the environmental hazard of production resulting from the failure of building structures (K_{ek}), and the coefficient of the influence of the aggressiveness of the production environment (K_{ag}):

$$K_b = Y_n \cdot K_{\text{ek}} \cdot K_{\text{ag}} \tag{2}$$

The primary purpose of the technical condition passport of a building was to contain information about the main technical parameters of the building (a precursor to BIM models) and answer whether it is possible to operate this building until the next inspection.

In the next 15 years, the situation related to the norms for assessing the technical condition of buildings and structures remained the same. In 2016–2017, two national standards were introduced - DSTU-N B V.1.2-18:2016 [8] and DSTU B V.2.6-210:2016 [9]. Standard [9] is the second edition of the normative document [6], which practically retained its structure with partially expanded calculation methods for assessing the load-bearing capacity of damaged steel elements. Standard [8] is a new document based on [5, 7]. Ideologically, the document is based on a visual assessment of the technical condition of building structures. Table 1 are presented for masonry structures, containing coefficients for reducing the load-bearing capacity of stone structures in the presence of damage, γ_t.

Table 1. Coefficient for reducing load-bearing capacity when forming force cracks from compressive forces (Adapted from Table V.3.2 DSTU-N B V.1.2-18:2016 [8]).

No.	Type of Damage	Coefficient γ_t for	
		Unreinforced Structures	Reinforced Structures
1	Cracks in individual bricks that do not intersect mortar joints	1,00	1,00
2	Hairline cracks intersecting no more than two rows of masonry	0,90	1,00
3	Same as above, intersecting no more than four rows of masonry, with no more than four cracks per 1 m width (thickness) of wall, column, or partition	0,75	0,90
4	Cracks with an opening up to 2 mm, intersecting no more than eight rows of masonry, with no more than four cracks per 1 m width (thickness) of wall, column, or partition	0,50	0,70
5	Same as above, intersecting more than eight rows	0,00	0,50

This table is borrowed from the Recommendations for Strengthening Masonry Structures in 1984 [10]. Given that information about the origin of these coefficient data was not found, using these coefficients without additional verification is not advisable. At the same time, the approach itself is exciting and may have further development in the Eurocode system.

The weakness of these two standards is the simultaneous application of both. It is explained by the fact that different developers worked on the standards. A positive aspect is that the two groups of developers agreed on specific points – such as the number of technical conditions now fixed at four technical conditions and their names. Standard [8] regarding the inspection of steel structures contains a direct reference to [9]. At the same time, the scope of application of the standard [9] has been expanded to include steel structures of buildings and structures of any purpose.

2 Comparison with the International Standard for the Evaluation of Operating Structures.

The main provisions of Ukrainian regulatory documents were compared with the international standard ISO 13822:2010 [11]. The general procedure for assessing the condition of existing structures is quite similar, and it does not make sense to pay attention to minor differences. Let us focus on significant differences. According to [9], the assessment of the technical condition is the determination of the level of damage to steel structures and the establishment of the category of its technical condition. According to Sect. 4.1 [8] the investigation of the object is the element of supervision that determines the technical condition of the object. Even though standard [8] in Sect. 1.2 regulates the inspection of objects to ensure standards [12, 13], which essentially corresponds to EN1990 [14] and ISO 2394 [15], this document does not contain information on determining the reliability level of existing structures. Thus, the assessment of the condition of existing structures comes down to the need for an expert to classify the structure into one of four technical conditions: 1 - normal, 2 - satisfactory, 3 - not suitable for regular use and 4 - emergency. A significant part of the document is a description of procedures for the scope and procedure of inspection work, depending on various situations, which does not cover all possible situations and sometimes contains information more typical of textbooks than regulatory documents. Also, tables are compiled for the main types of load-bearing structures (foundations, reinforced concrete, masonry and timber structures) to establish the category of the technical condition of the structure. A similar table is included in [9] to establish the technical condition of steel structures. Similar tables are absent in [11], while in section C.1, the expert is suggested to visually assess structures as “without defects”, “minor”, “severe”, etc.

The practice of using similar tables at the stage of preliminary assessment of existing structures in new European documents would allow for a reduction in decision-making time. Perhaps it is not necessary to introduce a division into technical conditions, but having materials for a preliminary assessment that would allow classifying defects into groups could allow more qualitative decision-making regarding the need for a detailed assessment.

For example, a deflection in the form of a separate element from the plane of the truss (Fig. 1), with values of $f_y \leq 15$ mm or $f_y/L \leq 1/750$, this structure can be used without a detailed analysis; if not, additional calculations should be performed, taking into account the geometric nonlinearity of the elements. The limit values of defects can be set in EN, with adjustments in National Annexes. or may be presented in reference documents to Eurocodes. In general, the use of the method of comparing geometric parameters of a defect with limit values (or relative geometric parameters of a defect, for example, the depth of the notch in the flange to the total width of the flange) to determine further actions in the study of a damaged structure is another feature that distinguishes Ukrainian standards from [11]. At the same time, the described "tabular" method of determining the technical condition of building structures sometimes turns into the final part of the assessment. The condition of a building or structure is assessed by the presence of a crack in the brickwork or the presence of horizontal bending of a steel beam, not by the influence of this defect on the reliability of the damaged structure. The authors of this article have seen conclusions where a house was recognized as an emergency due to frost damage to a wall to a depth of 30% of its total width without performing additional calculations, etc.

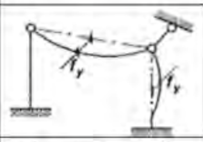
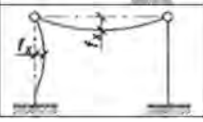
Defect Group	Number within the Group	Defect (Damage) Description	Sketch	Category according to 6.5.10	Allowable Limits in the Technical State		Note
					Normal	Satisfactory	
5	1	Overall deflection of the structure in the plane of the frame		Bd	$\frac{f_y}{l} \leq \frac{1}{750}$ $f_y \leq 15mm$	Verified by calculation	l - length of the bent structure
	2	Overall deflection of the structure in the plane of the frame		Bd	$\frac{f_x}{l} \leq \frac{1}{750}$ $f_x \leq 15mm$	The same	

Fig. 1. Excerpt from the table "Limit values of defects and damage" (Adapted from Table V.1 DSTU B V.2.6–210:2016 [9]).

According to [8], permanent loads g_p, in Pascals (Pa), from the weight of the coverings (overlays) are recommended to be determined, taking into account the results of uncovering the roof (enclosure) and the actual composition of its layers. The characteristic values of these loads are determined by weighing samples and processing the weighing results using the formula:

$$g_p = p_p \pm \mathrm{K} \cdot \frac{S_g}{\sqrt{m}}, \tag{3}$$

where $p_p = \frac{1}{m} \cdot \sum_{i=1}^{m} p_i$ is the arithmetic mean value of the weight of samples in Pascals (Pa);

$S_g = \sqrt{\frac{1}{m-1} \cdot \sum_{i=1}^{m} (p_i - p_n)^2}$ is the root mean square deviation of weighing results in Pascals (Pa);

p_i is the total weight of all layers of the enclosing structure in layer number i, Pa;
m is the number of samples (no less than 5);
K is the coefficient that considers the sample size, determined by Table 2.

Table 2. Coefficient K (Adapted from Table 6.2 DSTU-N B V.1.2-18:2016 [8]).

The number of samples *m*	K	The number of samples *m*	K	The number of samples *m*	K
5	2,13	9	1,86	25	1,71
6	2,02	12	1,80	30	1,70
7	1,94	15	1,76	40	1,68
8	1,89	20	1,73	60 and more	1,67

Note. For intermediate values of m, the coefficient K is determined by linear interpolation.

The "plus" sign in formula (3) is considered for the unfavourable effect of increased load, and the "minus" sign is considered for the favourable effect.

It is permissible to determine gp taking into account the non-uniform distribution of the permanent load over the surface of the enclosing structure using the formula:

$$g_p = p_p \pm \frac{1,64 \cdot S_g}{\sqrt{1 + 0,1 \cdot (L + B) + 0,006 \cdot L \cdot B}}, \tag{4}$$

L and B are the length and width of the load area of the calculated structure, measured in meters.

Obviously, not all accumulated experience of Ukrainian scientists in assessing the technical condition of existing structures is presented in regulatory documents. It is challenging to cover all research conducted over the past 30 years within one article. Therefore, we will focus on the activities of scientific groups and publications issued 10–30 years ago. Some provisions described in the State Standards for inspecting steel structures were developed by A. Perelmuter and published in the monograph [16]. Methods for refining cranes and atmospheric loads were developed, presumably with S. Pichugin, V. Pashynskyi, and other researchers [20]. The methodology for checking the load-bearing capacity of beams with horizontal deflection is based on the methodology of A. Rzhanitsyn [17] was additionally verified based on experimental tests by scientists from Poltava – S. Pichugin, V. Semko, and S. Hudz [18, 19]. The Poltava group also developed a methodology for calculating steel beams with one-sided notches in the flanges [21, 22]. According to the research, it was established that in steel beams with a symmetrical cross-section and one-sided notches in the flanges, additional stresses from torsion occur, and the magnitude of these stresses depends on the length of this notch. The formula will determine the maximum normal stresses in the section with a notch

$$\sigma_{max} = \sigma_{bend} + \left[0,12 \cdot ln\left(\frac{\ell_c}{\ell}\right) + 1\right] \cdot \sigma_{\varpi}, \tag{5}$$

where ℓ_c is the length of the notch; ℓ is the span of the beam; σ_{bend} is the normal bending stress determined by considering the actual geometric characteristics of the damaged section; σ_ω is the normal stress from warp torsion of the beam.

Subsequently, this methodology was refined in the works of O. Voskobiinyk [23]. The research on the behaviour of damaged steel-reinforced concrete structures was also conducted [23], and tables of allowable values for defect and damage parameters of bent and compressed steel-reinforced concrete elements were proposed, similar to the tables in DSTU [8].

Works by Z. Blikharskyy [24], V. Klymenko [25], O. Semko [26], and many others are dedicated to the assessment of the technical conditions of existing building structures. Research on corrosive damage to steel structures is the focus of studies by V. Korolov and O. Gibalenko [27]. Numerous researchers have contributed to investigating the stress-strain state of existing structures, including structures with damage or imperfections. However, these studies have yet to be incorporated into Ukraine's regulatory documents for various reasons.

An exciting direction related to the reliability of existing enclosing structures was initiated in the works of V. Pashynskyi and G. Farenyuk [28, 29]. A new research direction, thermal reliability of enclosing structures, was proposed. Thermal reliability refers to the ability of the structure to maintain its performance over a specified service life continuously. It was established [29] that the number of days per year during which thermal failure of the enclosing structure occurs under specific criteria is a convenient and illustrative indicator of thermal reliability.

The initiated direction has been continued in the works of V. Semko and M. Leshchenko, who investigated the thermal reliability of structures combining load-bearing and enclosing properties-walls with a frame made of thin-walled cold-formed steel elements. For this purpose, statistical characteristics of materials used in these structures were established [30]. The study [31] investigated the changes in strength and thermal conductivity of polystyrene concrete (which can be used as insulation in this technology) depending on its density. Using the obtained statistical data, methods for assessing the reliability of enclosing structures with cold-formed steel elements were developed according to various criteria [32–34]. Applying probabilistic approaches and risk theory also allowed the formulation of a method for standardizing the thermal resistance of enclosing structures based on a specified failure probability or estimating the probability of thermal failure for a particular design solution [35]. Determining the probability of failure-free operation of load-bearing elements made of cold-formed thin-walled steel profiles, including existing ones, is addressed in the eighth section of the work [36].

Due to the hostilities in Ukraine, the issue of assessing the reliability of damaged structures returns to the consideration of Ukrainian scientists. As already mentioned, A. Perelmuter and S. Pichugin published a paper dedicated to some peculiarities of calculating the reliability of damaged structures [37]. The article describes methodologies for considering the influence of the structure's previous operational history on its reliability level. It also emphasizes the importance of refining material properties and loads, providing illustrative examples.

3 Conclusions

Based on the conducted analytical study of various normative documents and scientific works, the following recommendations can be made:

1. The procedure for assessing existing structures presented in [11] could be enhanced with additional materials regarding types of damage to building structures. Additional information on the geometric parameters of these damages and their maximum dimensions could allow for quicker decision-making during the inspection stage. The availability of such tables would enable a broader range of experts to participate in the assessment process, and only defects and damages exceeding the sizes presented in reference tables would require the involvement of experts and additional investigations, if necessary, to implement measures to enhance the reliability of the structures.
2. It would be advisable to provide calculation methodologies for reliability coefficients under loads for permanent loads, including the weight of existing structures and finishing materials. The same applies to determining reliability coefficients based on material properties. This would allow for a more accurate assessment of the reliability of existing structures.
3. A large group of structures can perform a load-bearing function and an enclosing one—such as walls with frames made of cold-formed steel elements (or wooden elements), walls made of lightweight concrete blocks and others. The reliability of such structures needs to be considered from the perspective of failure probability based on the criteria of the first (or second) group of limit states and the criteria of thermal failure. Thermal failure can be the first step toward failure for these structures based on strength criteria. Since it may cause corrosion for steel elements, decay for wooden elements, or alter the strength properties of lightweight concretes due to significant moisture accumulation.

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Procedure for Generation of Finite Element Models of Steel Members from 3D Scanned Data

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Abstract. With rapid development of 3D scanning technologies and implementation of digital twinning and reverse engineering in the construction industry, it became possible for finite element simulations to facilitate analysis of measured geometries when it is needed. A new approach to generate 3D solid models using advanced techniques in the field of 3D scanning is introduced in this paper. Constructing three-dimensional (3D) finite element (FE) models with measured geometry of structures or structural elements can be technically difficult. To date, there is no robust automated approach to translate the data obtained from 3D scans directly into a model for FE analysis. This paper provides an overview on current applications of 3D scanning, and a case study that addresses the issue of processing three-dimensional point clouds that are generated from 3D scans of steel links. Another objective of this paper is to present a simple and practical procedure to convert point clouds into solid models that can be further used in FE analysis. Five distinct 3D scanning technologies were selected for the measurement of replaceable steel links to generate solid models based on the measured geometry. For the specific application addressed in this paper, the blue laser scanner with measuring arm has shown the most satisfactory results in terms of efficiency.

Keywords: 3D scanning · point clouds · steel links · solid models

1 Introduction

There are a variety of technologies for digitally acquiring the shape of 3D objects. The techniques work with many sensor types including optical, acoustic, laser scanning, radar, thermal, and seismic. A well-established classification divides them into two types: contact and non-contact [1]. Non-contact solutions can be further divided into two main categories, active and passive. There are a variety of typologies that fall under each of these categories.

The usual result obtained from measurements based on 3D scanning is represented by a considerable number of points, called in the literature point cloud [2]. The point cloud is a collection of points, defined as position by XYZ coordinates in a common system of reference, which reveals to the observer information about the spatial shape, position, and distribution of an object or group of objects. Other types of data obtained directly from the scanning process or based on the point cloud processing are polygon mesh models, surface models and solid CAD models.

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2 Current Applications and Directions

The potential use of 3D point clouds remains an emergent topic among researchers for a vast variety of applications in the field of civil engineering and construction industry. For example, Vacca et al. [3] presents an interesting approach to use the terrestrial laser scanner for monitoring the deformations and the damage of buildings.

A highly relevant contribution to this field is proposed by Funari et al. [4], developing a framework for digital twin generation of historic masonry structures based on point clouds. The paper has shown the benefits of being able to monitor in real-time the evolution of the behaviour of existing structures. The proposed procedure exploits the capabilities of Generative Programming, in which the user can interact with the code by modifying and/or implementing new capabilities with the aim of obtaining a solid model based on point clouds. Pepe et al. [5] presents a comprehensive comparison of latest-generation 3D scanners in reconstruction processes of elements belonging to Cultural Heritage. Angjeliu et al. [6] developed a simulation model for Digital Twin applications in historical masonry buildings and presented the integration between numerical and experimental data. For this scope the finite element structural model of the Cathedral of Milan was obtained based on photogrammetric geometric measurements, extensive in situ 3D scans (LIDAR) and other archive data. The analysis provided information on the distribution of the internal forces, displacements, and damage. Guarnieri et al. [7] proposed a 3D scan model-based structural analysis on a structure belonging to Cultural Heritage that was subjected to three different effects: self-weight, wind load and out off-plumb effect. Herban et al. [8] investigated an innovative approach to obtain the 3D model of a structure belonging to Cultural Heritage, based on spherical photogrammetry.

Hu et al. [9] proposed numerical modelling for landslide analysis based on scans with LIDAR. The paper extends literature on manual and automatic approaches for converting data from point clouds to FEM numerical models. Castellazzi et al. [10] proposed a new semi-automatic procedure, called CLOUD2FEM, to transform point clouds of complex objects to finite element models.

Xie et al. [11] developed a 3D modelling algorithm for tunnel deformation monitoring based also on terrestrial laser scanning (LIDAR). Cui et al. [12] developed another interesting approach for generating finite element mesh from 3D laser point clouds for tunnel structures. The point cloud model of the tunnel was acquired using terrestrial laser scanning and mobile laser scanning. Fernandez et al. [13] suggests numerical model development from 3D scans applied to corroded steel bars, in order to investigate the failure process and local effects on the pits.

Zhao et al. [14] presents a procedure for processing 3D point clouds that are generated from laser-based scanning of a cold-formed steel member into useful measurements of cross-section dimensions, as well as for use in finite element simulations of the as-measured geometry. The paper demonstrated the use of laser scans for dimension control providing comparisons to manual measurements and nominal manufactured specifications, in case of cold formed elements.

3 3D Scanning of Steel Links

3.1 Research Framework

The finite element method (FEM) is commonly adopted for numerical investigation of the behaviour of various structural components. The most refined analysis is currently considered the geometrically and materially nonlinear analysis with imperfections (GMNIA). As it is clearly stated by its name, the analysis method requires modelling of geometrical imperfections, which is particularly important for numerical verification of buckling resistance. The conventional FE modelling of geometrical imperfections of an experimental specimen involves:

1) Modelling the "perfect" shape of the specimen using nominal or measured cross-section dimensions.
2) Modelling of the geometrical imperfections by applying an appropriately scaled deviation obtained from buckling analysis. As imperfections are difficult to measure, they are usually obtained from literature or specific codes (e.g. EN 1993-1-5).

The use of 3D scanning can simplify the process of FE modelling due to the fact that the point cloud of the specimen includes the geometry and also the initial imperfections that can be used directly in the numerical analysis, if steps are taken to post-process the point cloud into a model supported by the FE analysis software.

3.2 Experimental Specimens

In the framework of the HYLINK research project [15], and for the scope of this paper, it was proposed to measure the geometry and initial imperfections of replaceable steel links using 3D scanning technology and to develop a numerical model for validation of the experimental tests. The test specimens that were investigated are presented in Table 1 and Fig. 1. A total number of three steel links, with and without stiffeners were subjected to cyclic tests. A schematic and a typical longitudinal section view of a link is illustrated below.

Table 1. Characteristics of experimental link specimen.

Specimen	Stiffened sides	Steel grade	Dimensions
S-C	0	1.4404	$250 \times 140 \times 12 \times 8$
S-2DS-C1	2	1.4404	$250 \times 140 \times 12 \times 8$
S-2DS-C2	2	1.4404	$250 \times 140 \times 12 \times 8$

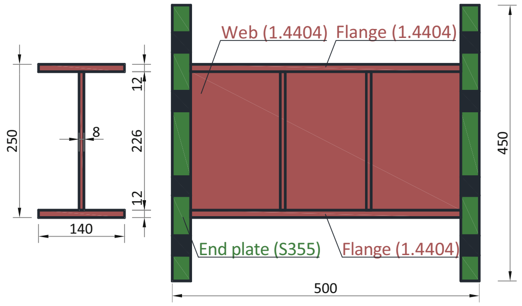

Fig. 1. Geometry of the link specimens.

3.3 3D Scanning of the Steel Links

For the aim of measuring the geometry and initial imperfections of the steel links, 5 different scanners (Table 2) based on 3 scanning principles (LiDAR, blue laser, and white structured light) were selected and applied to compare their workflow, accuracy, and time demand for obtaining the measurements (Table 3).

Table 2. Technical specifications of the used scanners.

Data acquisition device	Scanning technology	Scanner type	Accuracy (mm)	Data acquisition rate (pts/sec)	Stand-off distance (mm)
Z+F IMAGER	LIDAR	static	0.1	1.016 mill.	500
HEXAGON	Blue laser	measuring arm	0.01	1.2 mill.	115
EinScan Pro HD	White light	handheld	0.04	3 mill.	500
CREAFORM	Blue laser	handheld	0.04	0.48 mill.	300
IPHONE 14 PRO	LIDAR	smartphone	10	–	100

Table 3. Comparison between the five scanner systems.

Data acquisition device	Complete 360° scan capability	Duration/ scan (min.)	Calibration	Targets	Special lighting conditions	Sensitivity to reflective surfaces
Z+F IMAGER	NO	30-40	automatic	YES	NO	NO
HEXAGON	NO	20-25	manual	NO	NO	NO
EinScan Pro HD	YES	80-90	manual	YES	YES	YES
CREAFORM	YES	30-40	manual	YES	NO	NO
IPHONE 14 PRO	NO	15-20	N/A	NO	YES	YES

As shown above each technology has positive and negative aspects that can influence the final raw product of the scans – the point cloud. In case of three (Z+F, Hexagon, Iphone) out of the five scanners, the technology implies that the measured specimen keeps its initial position, which leads to unscanned areas. The measurement time varies between 15–20 min in the case of the smartphone and up to 90 min for the structured light scanner. Most technologies require manual pre-measurement calibration, excepting the terrestrial laser scanner (TLS) Z+F IMAGER and the smartphone. Reflective targets are also demanded excepting the Hexagon Absolute Arm and Iphone. Sensitivity to reflective surfaces is an aspect observed during the scans just in the case of the structured light scanner and smartphone.

4 Post-processing of the Scanned Data and Finite Element Modelling

4.1 General

From the structural perspective, point clouds cannot be used directly for 3D modelling and for numerical analyses because they are formed by many discrete points defined by three-dimensional coordinates. To effectively use the geometric data derived from the 3D scanning measurements, it is necessary to perform operations that transform the point cloud into a 3D model. The procedure to obtain a solid model compatible with a FEA software (for example Abaqus) from point clouds could be sometimes sophisticated (Fig. 2).

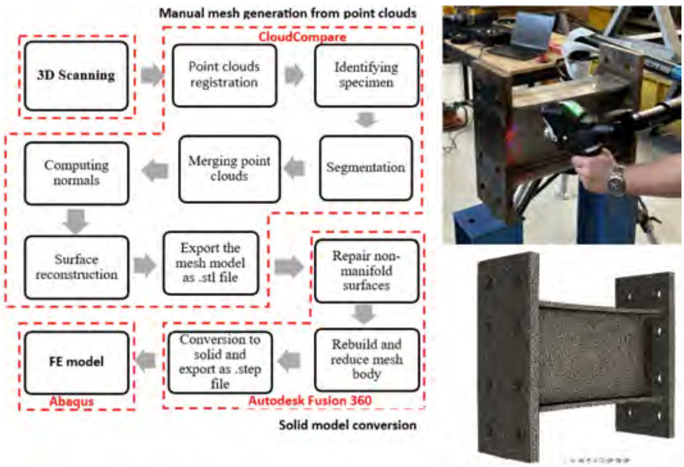

Fig. 2. Workflow of post-processing point clouds and generating solid models

Fortunately, the current features of most of the post-processing software bundled with 3D scanners, include the possibility to convert in a semi-automatic manner the point cloud into a mesh, reducing the time spent for processing purposes. However, for the moment LiDAR terrestrial laser scanners do not offer a converter software. In comparison with the other selected scanners, the Z+F LaserControl software facilitates just the point cloud alignment, while the exported formats are also point clouds. Other third-party software, such as CloudCompare need to be used for specific post-processing steps to obtain a mesh model, and Autodesk Fusion 360 to obtain the final solid model.

4.2 Manual Mesh Generation from Point Clouds

In case of the point clouds obtained from the TLS, several steps were considered to obtain a mesh model. First, the aligned point cloud was exported from Z+F LaserControl as e57 file format and imported in the open-source software CloudCompare for post-processing. The first step consisted in identifying the measured specimen in the dense point cloud of each of the six scanning stations. For redundant data removal, segmentation was used in this case, by defining 2D polygons in the point cloud. Next, a single entity was generated. Since the measurements took place in laboratory conditions, and the scanned specimens were relatively small, a manual noise reduction through further segmentation was chosen instead of other removal procedures.

In order to obtain the mesh model of the link, the next step was to compute ÿ normal on the point cloud. The normal vector to a surface is a vector which is perpendicular to the surface at a given point. When normal vectors are considered on closed surfaces as in this case, the inward-pointing normal (pointing towards the interior of the surface) and outward-pointing normal need to be distinguished. By considering the normal vectors to the surface, the "Poisson surface reconstruction" method [16] was used to create the mesh model (Fig. 3). The final mesh model can be then exported to other programs such as Meshlab, FreeCad, Autodesk Fusion 360, and even Abaqus, as an unstructured triangulated surface (stereolithography).

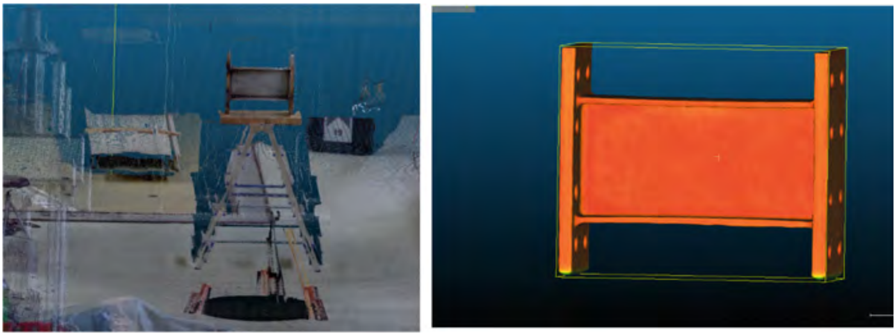

Fig. 3. Obtaining the mesh model of the link in CloudCompare

The four other used scanning devices (EinScan, Creaform, Hexagon Absolute Arm, iPhone 14 PRO) enabled a more straight-forward procedure to obtain the.stl file format and could directly export the mesh model from the embedded software (Vxelements, Polycam, Solid Edge, Inspire, respectively).

As a further step, it was investigated if the stereolithography data (.stl file) exported from these programs can be imported in the FEM software (Abaqus) and used in a numerical analysis. The stereolithography data is imported into Abaqus as an orphan mesh, and it is not thus editable. An orphan mesh part contains no feature information and is basically a collection of nodes, elements, surfaces, and sets with no associated geometry. Abaqus/CAE enables the conversion of an orphan mesh to editable geometry, but during the conversion process, it was observed that the models were missing elements and were not complete. This issue is related to the fact that the raw stereolithography data contain mesh models that are not closed properly.

4.3 Generating Solid Models from 3D Surface Models

To use data obtained from 3D scanning in Abaqus CAE it is important that the imported model to be a solid that can be assigned volume and weight. These solids are called manifold solids. The 3D models, directly constructed by the programs (Vxelements, Solid Edge, Polycam) that are offered for post-processing with the presented scanners, are only individual triangular 3D surfaces. Thus, it was necessary to identify a third-party software in which the 3D surface models (mesh models) can be imported for repairing and improvement of the mesh and eventually to obtain the solid model.

A 3D surface model or simply stated as mesh model is generally a collection of multiple individual triangular planes formed by connecting points in the point cloud. As the number of points increases, the point cloud is more likely to have individual planes that are intersecting each other, or holes which can cause issues for the later processes. These surfaces are defined as non-manifold surfaces. A manifold 3D surface is defined as a 3D surface that encloses itself and does not have any gaps and self-intersections.

Therefore, to ensure that the 3D surface model can be transformed into solid, any holes in the 3D surface model need to be closed. Repair of non-manifold 3D models is important because it will directly affect whether or not the model is able to be used in FEM software packages.

The capabilities of three open-source programs that are supporting semi-automatic repair solution for non-manifold 3D models were investigated: Autodesk Fusion 360, FreeCad and Meshlab. The three programs were all successful in repairing the models, but the solid conversion was only managed in Autodesk Fusion 360. After importing the stereolithography data, the non-manifold surfaces were repaired successfully, and the mesh body was entirely rebuilt while preserving sharp edges (Fig. 4).

The repaired manifold 3D surface was then scaled to the actual size of the specimen. Due to the high complexity of the obtained manifold 3D surface, it was necessary to reduce the mesh size. Autodesk Fusion 360 enables a semi-automated conversion procedure of the mesh model to a solid model. From the three methods available, the "Faceted method" has shown the more reliable results. The final output is a solid model with virtual topology that can be exported as a common file format for 3D models (.step file) to the FEM software (Abaqus). In this manner the measured geometry and initial geometric imperfections of the specimens are readily embedded in the numerical model for FE analysis.

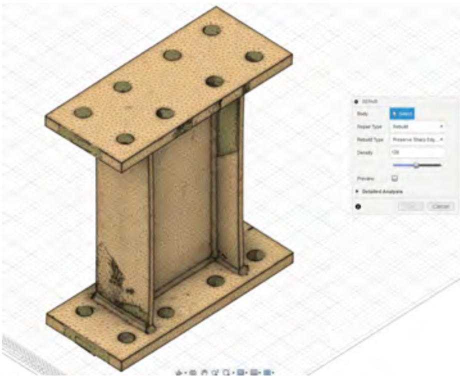

Fig. 4. Rebuild mesh body function.

4.4 FE Model

After importing the model in Abaqus, it was observed that for discretizing the model with flexible and even sizes of elements, the virtual topology needs to be combined before the discretization by using the tool Virtual Topology – Automatic create. Since boundary conditions and loads can only be assigned at vertexes and edges, some of them might need to be restored using the tool Virtual Topology – Restore entities. The vertexes and edges are also the baselines for discretization.

Free meshing with tetrahedral elements was used in this application and the FE mesh model was successfully obtained as shown in Fig. 5.

Fig. 5. The FE mesh of the model.

5 Conclusions

FE modelling based on data obtained from 3D scanning is more versatile in comparison to conventional FE modelling and can reflect more accurately the real magnitude and shape of the geometric imperfections.

Further research is still needed to validate the latter assumption, by using the FE model obtained from 3D scanning in a numerical analysis and comparing the results with experimental data.

The advance of 3D scanning technologies and post-processing programs in the future may also enhance its application in FEM. The development of software and computational ability of PC would also benefit the accuracy and efficiency in reconstructing 3D models of complicated structures. All the procedures of point cloud alignment, 3D surface model construction, repair of models, and conversion in a solid model may be integrated into a single program in the future to make the post-processing stage fully automatic.

Terrestrial laser scanning technology (LiDAR) has proven highly accurate and independent of the lighting conditions of the surroundings and surface reflectiveness of the scanned object. However, it is not the most reliable option from an economic point of view and has the disadvantage of the need of a third-party program to obtain the 3D surface model (initial mesh model) from the point cloud.

Two different blue laser scanners were investigated within this work: with measuring arm and handheld. The blue laser scanner with measuring arm does not imply the use of targets on the measured specimen, but his scanning range is conditioned by the length of the measuring range, and the costs of this technology rise to six-figure values. Furthermore, the 3D surface models obtained directly from the embedded software have shown high quality in terms of measured dimensional values and imperfections. The handheld blue laser scanner was more flexible in use, being able to scan the whole surface of the specimens (allowing to change the initial position of the specimen). Also, the obtained 3D surface models were highly accurate, and the technology is more economically reliable. However, a major drawback is the necessity to use reflective targets on the measured specimen that can be time-consuming.

The structured light scanner had a similar accuracy to the blue laser scanners and the TLS, but the obtained 3D surface model is less qualitative, this technology being more sensitive to the lighting conditions and surface reflectiveness. The actual measuring time was longer and the number of used targets on the specimens was higher. The quality-price ratio of such a device is still satisfactory.

The smartphone LiDAR scanner is still in a continuous development stage and has proven because of this reason a much lower accuracy than the other devices. Hopefully, in the near future it will be considered a reliable alternative for large-scale use due to its low price and versatility in obtaining the 3D surface model directly.

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The Behavior of Heat-Damaged RC Beams Reinforced Internally with CFRP Strips

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Abstract. When an RC (reinforced concrete) structure is prone to a very high temperature, the structure severely deteriorates; the reasons for this are: a) the degradation in the products of the cement hydration, b) the production of vapor's pressure, and c) the incompatible change in the volumes of the components of concrete when the temperature is higher than 500 °C. Nevertheless, the structures damaged severely by excessive heat can be greatly able to re-have their original performance and qualities back if they are strengthened in shear with laminated CFRP (a short form for carbon fiber-reinforcement polymers) composites. However, the efficiency of this method is menaced because of two setbacks: 1) delamination, and 2) anchorage. This method aimed to examine its efficacy in reinforcing-in-flexural concrete beams, whether mainly or additionally, prior to and post being exposed to very high temperatures. In this paper, the study parameters were: 1) the CFRP sheet's length of CFRP; and 2) the exposed temperature. Also, the researchers took into consideration to monitor: the structure's behavior, the ultimate capacity of loading, the correspondent-to-loading deflections, toughness, and elastic stiffness. This research paper found that using internally installed sheets of CFRP for flexural strengthening proved to be highly efficient in damaged-by-heat RC beams.

Keywords: Internal CFRP Strips · Flexural · RC Beams · Elevated Temperature · CFRP

1 Introduction

Throughout the world, the CFRP laminates are widely utilized to reinforce/retrofit currently-standing RC structural members. Usually, the externally installed laminates of CFRP are utilized to externally reinforce/mend RC beams, whether in flexure or shear. Experimentally, it has been found that the delamination of the externally reinforced-with-CFRP concrete beams encountered de-bonding failure, resulting from the detachment of CFRP from concrete at the concrete-CFRP interface [1–3]. The CFRP materials have had the potential to pioneer the reinforcing/repairing businesses because they are highly strong in tension, although this strength is not used in full because of delamination of CFRP, the brittleness in the tensile performance, and overloading the mended/ reinforced RC beams [4].

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The practitioners in the field of construction employed externally installed CFRP laminates to additionally reinforce/mend RC members in flexure and shear. Generally, the efficacy of employing CFRP depends completely on the way this material is attached to the concrete. Nevertheless, a great number of reports mentioned that the reinforced-with-CFRP structures usually fail in de-bonding mode, where the CFRP material detaches prematurely from concrete [5]. Many researchers have experimentally proven that the externally installed CFRP laminates much enhanced the RC structural strength in shear, flexure, or both [6–8]. The problem of CFRP's detachment is an ongoing issue, particularly at locations with high stress or at the corners of CFRP, even when the laminates are adhered to recommended-by-manufacturer substances [9–13]. In case of overloading a building or removing one of its pillars, the building becomes deficient and needs to be fixed to retrieve its original strengths, whether in flexure, shear, or both. At this point, it must be assured that the reinforcing processes, in shear and flexure, should be performed at the same time in order to have a ductile form of failure [14, 15].

RC beams and other structures may encounter deformation, or even damage, when they are exposed to extremely high temperatures; as this kind of temperature causes a degradation in many of the mechanical qualities of concrete and reinforcing steel, which redistributes the developed stresses within the beam [16]. Researchers have concluded that utilizing external laminates of CFRP to strengthen/repair damaged-by-heat beams regained, to some extent, the beams' capacity of flexural strength and enhanced their performance in shear. The laminates of CFRP have gained good acceptance, and are favored to be used more than steel, due to their: resistance-to-corrosion, simple erection and handling, durability, high strength, cost-effectiveness, great strength-weight ratio, and capability of withstanding harsh environments [1, 17]. In order to judge the effectiveness of a material in reinforcing and/or retrofitting damaged-by-heat structures, the following factors must be taken into consideration: type utilized [18]; capability of resisting extreme temperatures [19]; the employed method of analysis [20, 21]; ability to resist energy integrity [22], the utilized method of anchorage [23]; conditions of heating [24]; type and size of employed fibers and severity of damage [25–27]; in addition to the reinforced-with-CFRP bridges' factors of safety [28].

Some concrete buildings are often prone to frequent heating-cooling cycles which degrade substantially, the quality of concrete within structures; thus, it is imperative to take such cycles when planning to design buildings like these, such as platforms for launching rockets; and nuclear plants for producing power [29, 30]. It is stipulated that concrete stays intact and preserves its qualities when exposed to a temperature below 300 °C; otherwise, it begins to lose its intactness when the exposure temperature exceeds 500 °C. Further, concrete is subject to drastic alterations in its qualities when it is prone to a fire attack which is distinguished rabidly. The reason for this is that the temperature of the core of concrete is way different from the temperature at the surface; this temperature variation produces tensile stresses on the concrete's surface which result in many incompatible expansion-retraction movements in the cementitious paste from one side and aggregates from the other side. In consequence, cracks emerge within the concrete's surface. The magnitude of damage within concrete structural elements is governed by several factors, for example: size of structure, type of cement, utilized type of aggregates, content of moisture within concrete, frequency and times that a structure is exposed to high levels of heat, the way used for cooling, and the highest level of exposure temperature [31].

2 Methodology and Used Materials

2.1 Constructing the Specimens

A total of eight concrete beam specimens have been built, having: a cross-section of (150 × 200) mm, and a length of (1100) mm total. The beam specimens were examined as they were subject to a four points loading, as simply supported (Fig. 1). The bottom side of the specimens was strengthened with two (∅10) steel bars, while the upper side was strengthened with two (∅10) steel bars (Fig. 1). Loading was applied using concentrated loading applied by a hydraulic jacket of 2000 kN capacity and beams were supported at 50 mm from each end.

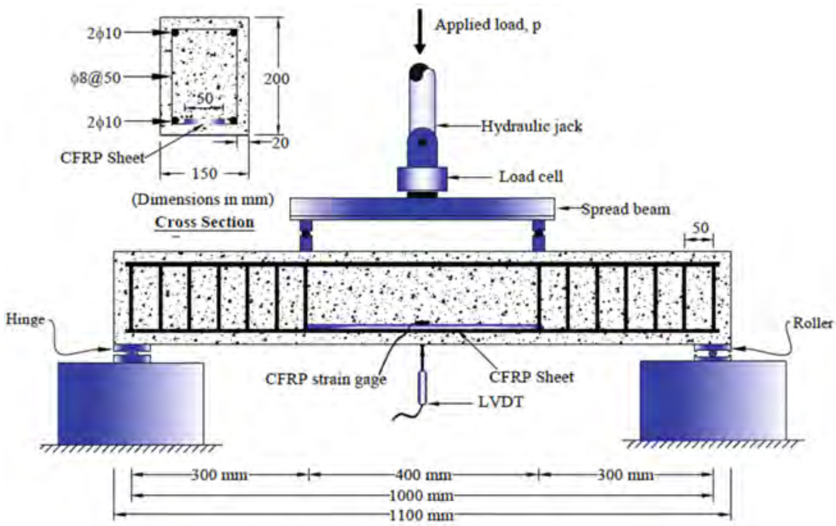


Fig. 1. Specimens test setup, reinforcement, dimensions, and instrumentations.

Strengthening was done using 50 mm width CFRP strips positioned internally on the top of the bottom main reinforcement with their strain values measured using an internally positioned strain gauge within the beam tensile zone, as presented in Fig. 2. The strengthening steel bars were supported and fixed in position by stirrups having a diameter of 8 mm placed at 50 mm away in the shear's span. Moreover, each beam specimen was equipped, at the flexural (bottom) side's bars, with a CFRP strip; these strips had the same width (of 50 mm) but were different lengths, namely: 400 mm, 600 mm, and 800 mm (Fig. 2). The qualities and the designations of the experimental beam specimens are elaborated, in summary, in Table 1.

2.2 Properties of the Materials

To make the experimental work more accurate, all of the specimens were built utilizing the same concrete mix which complied with the ACI design code of mixtures [32]. The concrete mix was made of ordinary type I Portland cement (422 kg/m^3), fine aggregates (crushed) (621 kg/m^3), coarse aggregates (crushed) (706 kg/m^3), and tap (fresh) water (147.6 kg/m^3); this mix was designed to achieve 28-day cylindrical strengths of 4.31 MPa in tension and 50 MPa in compression, at 23 °C, and also to have an 80 mm slump. As for the reinforcing bars of steel, their type was grade 60 and had a strength of yielding reaching 420 MPa. As for the sheets of CFRP, they were SikaWrap® −300 °C, made by Sika; while the adhesive's type was (Sikadur®-330), respectively, made by SIKA Fabric thickness of 0.167 mm (based on fiber content); Fiber Density of 1.82 g/cm^3; Tensile Modulus of 230,000 N/mm^2; Tensile Strength of 4,000 N/mm^2; Elongation break of 1.67%.

(a) $L_f = 400$ mm

(b) $L_f = 600$ mm

(c) $L_f = 800$ mm

Fig. 2. CFRP strips internal attachment at the beam's bottom tensile zone (width = 50 mm).

2.3 Mixing of Specimens and Heat Treatment

The process went as follows: the starting step was soaking the inner side, of the 0.15 m^3-capacity tilting drum mixer, with water. Then, upon running, the mixer was fed with the full quantity of coarse aggregates and some amount of the water already used for soaking. Next, the mixer was fed, in a step-by-step manner, with the ingredients of cement, fine aggregates, and water. Later, the last amount of water and a super-plasticizing material were put in the mixer. The last step was to mix the materials for five minutes before they were poured into (150 × 200 × 1100 mm) wooden molds for molding; then, they were put for compaction utilizing an electrical vibrator. After twenty-four hours of molding, the beam specimens were moved out of the molds, and they were immersed for twenty-eight days in a tank filled with lime water for curing.

The heat treatment process was performed by utilizing an easy-to-control automatic electrical furnace (Fig. 3). The specimens were heated at temperatures of 150 °C, 250 °C, and 500 °C for 120 min. Then, the heated specimens were allowed to self-cool inside the furnace.

Table 1. The details and results tested beams.

Group	Specimen	T, °C	L_{CFRP}, mm	P_u, kN	Δ_u, mm	ε_{CFRP}, $\mu\varepsilon$	$\varepsilon_{CFRP}/\varepsilon_{fu}$ (%)
1	BT23F0	23	None	116.8	12.8	–	–
	BT23F400		400	141.8	15.6	7045	41.8
	BT23F600		600	172.6	18.3	9222	55.1
	BT23F800		800	206.1	21.2	12283	73.4
2	BT23F0	23	400	141.8	15.6	7045	41.8
	BT150F400	150		112.1	13.5	5790	34.7
	BT250F600	250		93.0	12.3	4254	25.5
	BT500F800	500		72.1	11.6	3716	22.4

Note: L_{CFRP} and ε_{CFRP} are the CFRP length and strain, P_u and Δ_u are the ultimate load and deflection, ε_{fu} is the ultimate strain in CFRP strips of 16700 με

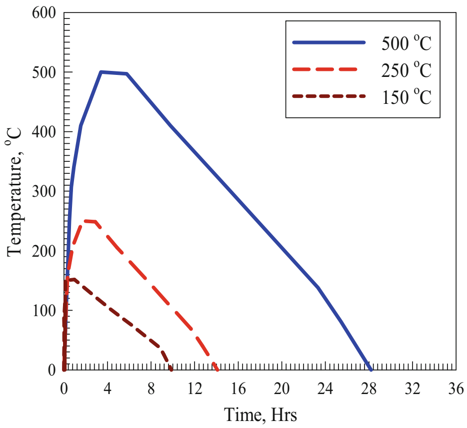


Fig. 3. The furnace time-temperature timetable.

2.4 Test Setup and Instrumentation

As previously mentioned, the whole beam specimens were simply supported and exposed to s four-point loading (Fig. 1). To make sure that the specimens would encounter a shear mode of failure in the shear's span, the shear's span-to-depth ratio (a/d) was made 1.7. A special actuator was employed to exert loading while controlling the servo, utilizing a special system for the acquisition of data. As for instrumentation, an LVDT (a contraction for linear variable displacement transducer) was employed to record the value of deflection at the middle of the span. Additionally, two strain gauges were employed to record the values of strain at the ends of the beam; these gauges were mounted on the at-the-center CFRP strip's sides (Fig. 1).

3 Results and Discussion

3.1 Mode of Failure

To analyze the beam specimens' flexural behavior more precisely, the cracks' appearance was recorded at different values of load steps. The modes of failure encountered by the control (with no reinforcement) beam are shown in Fig. 4, and those encountered by the reinforced beam specimens are in Fig. 5. The control beam witnessed its initial flexural crack at its mid-span; this crack was succeeded by more cracks in other places. Later, the beam encountered a de-bonding mode of failure located at the externally-bonded sheet of CFRP.

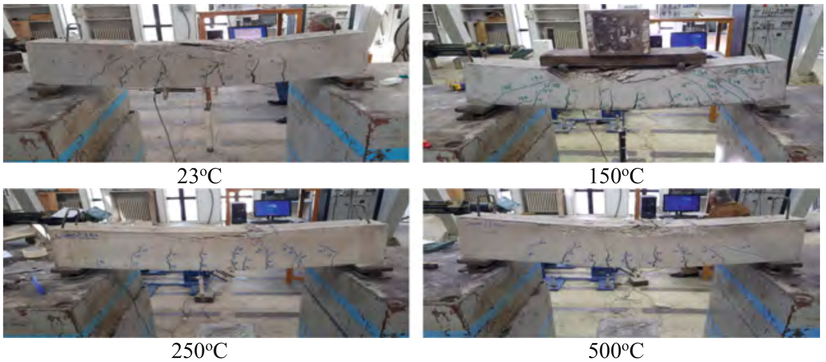


Fig. 4. The effect of temperature on the failure mode of the control specimen.

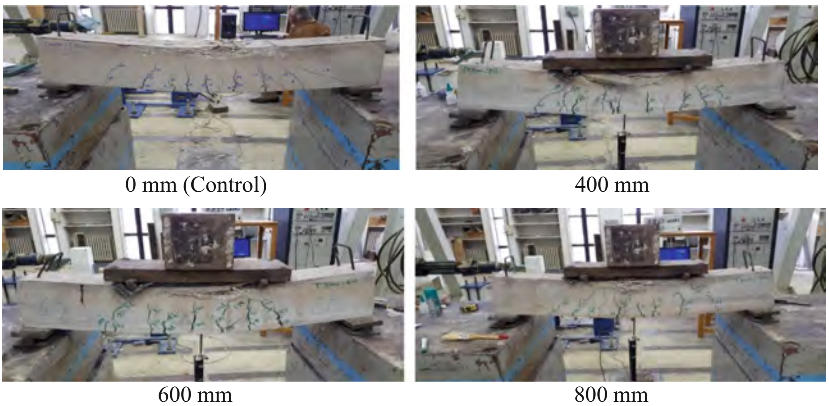
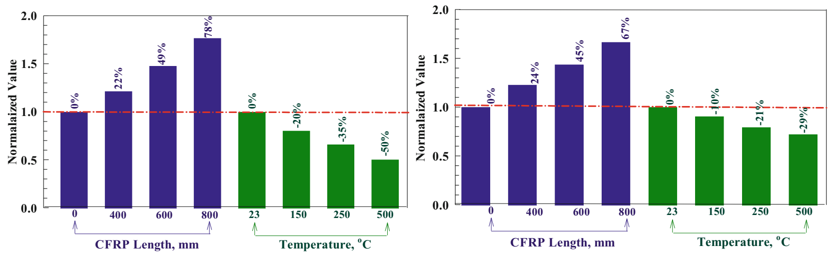


Fig. 5. The effect of CFRP length on failure mode.

Figure 5 showed that the length of the CFRP sheet governed the intensity of cracks, their length, and the way they were distributed. Figure 5 indicated that the cracks' intensity enhanced when the exposure temperature was raised, while Fig. 5 indicated that the propagation of cracks enhanced when the length of the CFRP was increased; this could be because of the CFRP sheet's capability of bridging the emerged cracks by availing adequate length. This is possibly confirmed as the internally installed CFRP sheets stop unexpected sheets' detachment; this is evidence that the internally bonded sheets of CFRP have improved the structural behavior by seizing flexural cracking.

3.2 Failure Loads and Corresponding Deflection

Table 1 demonstrates the ultimate values of the beam specimens' strength and resultant deflection. The values of failure load and resultant deflection were modified as per the ones obtained from the control beam specimen (Fig. 6). As for the internally strengthened with CFRP, utilizing CFRP sheets with lengths of 400 mm, 600 mm, and 800 mm raised the ultimate value of strength by 21%, 48%, and 77%, in respective order; these values were 1.97 times the values gotten from the externally-strengthened beam specimens (Fig. 6(a)); while the same CFRP sheets enhanced the values of the resultant deflection by 24%, 45%, and 67%, corresponding to 2.22 times the values gotten from the externally-reinforced specimens (Fig. 6(b)). As for the temperature's influence on the failure load (Fig. 6(a)) (compared with the beam specimens at 23 °C), the load of failure lessened: by 19% at 150 °C, by 34% at 250 °C, and by 49% at 500 °C.



(a) Failure load (b) Failure deflection

Fig. 6. The ultimate load and deflection behavior.

3.3 Load-Deflection Behavior

Figure 7, which elucidates graphically the beam specimens' load-deflection behavior, indicates that the graph has two parts: the before-cracking part, represented by a straight line, while the second part represents the after-cracking, where the slope noticeably changed post-emergence of cracks in flexure. The reinforced-with-CFRP beam specimens, whether internally or externally, had a better capacity for load carrying than the control (without reinforcement) beam specimen. Further, the load-deflection graphs also indicated when the area of bonding was raised, the beams' behavior was much improved; to put it differently, the beam specimens strengthened with an 800-mm-long sheet of CFRP showed a better behavior than those strengthened with a 400-mm-long sheet of CFRP. The outcomes of a conducted comparison analysis indicated that the strengthened-with-CFRP beam specimens demonstrated better behavior than the control specimen, in regard to stiffness, at-ultimate strength, and at-ultimate deflection. Moreover, the latter characteristics improved more when the CFRP sheet's length was raised. Furthermore, at a given length of the CFRP sheet, the internally strengthened beam specimens had better levels of stiffness, at-ultimate strength, and at-ultimate deflection, in comparison with the externally-reinforced specimens.

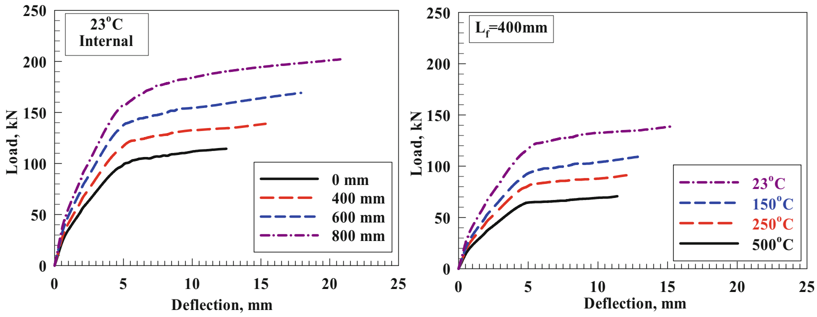


Fig. 7. Load-deflection curves.

4 Conclusions

In light of the achieved outcomes, the next conclusions have been extracted:

1) Internally bonded sheets proved to be highly effective because it was simple to adopt and economical because neither anchoring nor adhering was needed; the reinforcing sheets could be handled and shaped easily, and they could be attached using regular tape at the upper and lower surfaces of steel. It should be affirmed that the CFRP sheets could not be out of position while casting the concrete.
2) The research paper in hand proved that utilizing the internally attached sheets of CFRP was viable and feasible in reinforcing/mending damaged-by-heat RC beams and improving their performance because this method eliminated the failure in de-bonding.
3) When subjected to temperatures less than 150 °C and higher than 250 °C, the RC beams encountered a reduction in stiffness and shear capacity; also, the concrete encountered numerous cracks with no spalling.

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Energy Systems and Structures

Influence of Adaptive Controlling Strategies of Floating Offshore Wind Turbine on Corrosion Fatigue Deterioration of Supporting Towers

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Abstract. Floating offshore wind turbines (FOWTs) demonstrate very promising potential in unlocking the plentiful wind resource in deep-water oceans. Meanwhile, the combination of the harsh marine environment and strong dynamics complicate the long-term deterioration of FOWT-supporting towers, specifically the escalating corrosion fatigue (C-F) coupled deterioration in critical connections. Unlike traditional engineering structures, an interoperable control is available in FOWTs, such as the pitching, yawing and torque controllers, which can mitigate structural oscillation and loads. With the recent advances in smart sensing, a better prognosis of current and future deterioration can be guaranteed with increasingly accessible data. Thus, a refined adaptive control strategy is hence deemed essential based on the site-specific data, to curb the operation and maintenance (O&M) costs of FOWT towers based on the structural condition. The present work elaborates on the influence of various adaptive controlling strategies of FOWTs on the C-F deterioration of supporting towers, lending itself to preliminary references for balanced trade-offs between power generation and structural reliability. Multiphysics simulations of FOWTs are initially carried out to establish fatigue stress spectra from site-specific wind-wave distribution, using various types of control strategies. Structural reliability assessment is then conducted by incorporating the spectra into a time-variant C-F deterioration model in which the ambient corrosivity is accounted for. The result suggests a compelling C-F deterioration faced by FOWT towers due to strong wind-wave loads, high corrosivity and improved structural flexibility. More critically, the finding underscores the apparent influence of controlling strategies on the C-F deterioration of FOWT structures, especially under certain regimes of wind velocities. In addition, preliminary but innovative perspectives are elucidated on the delicate balance and conflict between generation efficiency and structural reliability.

Keywords: Floating offshore wind turbine (FOWT) · Adaptive Control · Supporting Tower · Corrosion Fatigue (C-F) · Structural Reliability

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1 Introduction

Floating offshore wind turbines (FOWTs) enable the exploitation of redundant renewable energy in deep waters, but they face structural challenges from corrosion fatigue (C-F) of bolts in ring-flange [1] These bolts are crucial for the tower and nacelle assemblies, but suffer from cyclic stresses and marine corrosion. As a result, the coupling effect of corrosion and fatigue (usually called as corrosion fatigue) will accelerate the deterioration process, and risk premature failure of bolts [2]. The prominence of C-F issue in FOWTs has been illustrated in a list of studies [3]. Thus, an interdisciplinary approach is needed, involving improvements in materials engineering, stress analysis, and predictive maintenance strategies to increase the durability and reliability of FOWTs (Fig. 1).

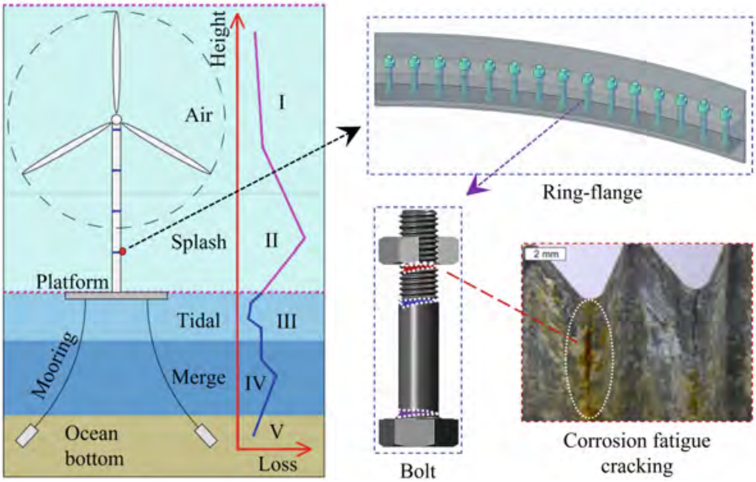

Fig. 1. Corrosion fatigue of high-strength both in ring-flange of FOWT towers.

Mitigating fatigue deterioration in wind turbine towers is a multi-faceted challenge that necessitates a deep understanding of both the physical phenomena involved and the innovative control strategies that can be applied. From the state-of-the-art notes provided and supplemented by recent scholarly articles, it is evident that proactive and adaptive control strategies form the backbone of mitigating such fatigue. These strategies include individual pitch control, where each blade's pitch angle is independently controlled to reduce asymmetric loads and thus mitigate fatigue [4]. Another method involves the use of online structural health monitoring systems that adaptively adjust operational parameters to reduce stress and enhance the service life of the structure [5]. Moreover, preventive control strategies are being explored, leveraging advanced forecasting techniques to predict and prepare for incoming gusts or turbulence, thus allowing preemptive adjustments that minimize fatigue loads. These methods aim to strike a balance between optimal energy capture and load reduction, thereby extending the service life of turbine components. The integration of real-time data analytics into control systems is also increasingly common, facilitating dynamic adjustments based on immediate assessments of structural integrity and environmental conditions.

This work investigates how adaptive controlling strategies can reduce the corrosion fatigue (C-F) damage of supporting towers in floating offshore wind turbines (FOWTs), which affects their operational dynamics and structural integrity. The paper adopts a systematic approach, starting with an overview of the challenges and opportunities of FOWTs, followed by a comprehensive analysis of different controlling strategies, their implementation, and their impact on the C-F performance of the towers. The study then presents a multi-physics simulation framework that integrates structural, hydrodynamic, aerodynamic, and C-F models to evaluate the effectiveness of the controlling strategies. A probabilistic model is also developed to assess the uncertainty and reliability of the C-F life prediction. The paper concludes with a discussion of the main findings and their implications for the future design and operation of FOWTs.

2 Multi-physics Simulation

2.1 Probabilistic Corrosion Fatigue Modelling

In order to incorporate the degradation in fatigue performance by corrosion, a time-variant probability-stress-life (t-PSN) model is developed according to the report [8], as shown in Fig. 2. The three-dimensional representation correlates fatigue strength with loading cycles and service life, taking into account both the mean and the statistical variability (±2σ) around this mean, thereby encapsulating the expected range of material behavior under operational cyclic stress.

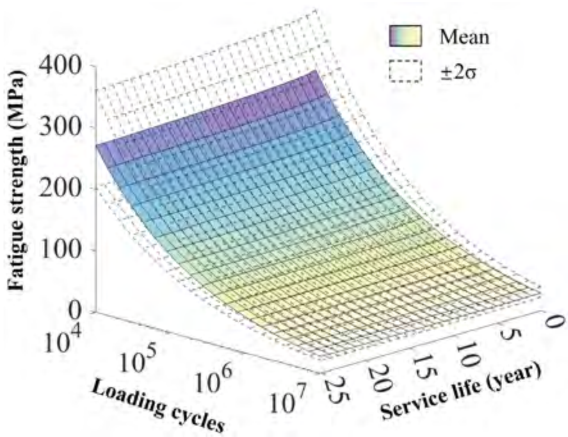

Fig. 2. Probabilistic corrosion fatigue modelling of high-strength bolts.

The proposed t-PSN model adeptly captures the diminishing fatigue strength as a function of time, attributing this decline not solely to the repetitive loading but also to the progressive corrosion that inherently accompanies service in corrosive environments such as marine atmospheres. As the bolt undergoes cyclic stress, the concurrent corrosive effect impairs its resistance to fatigue, accelerating the deterioration process beyond what would be expected from mechanical fatigue alone. The shaded area delineated by the $\pm 2\sigma$ boundaries on the plot emphasizes the uncertainty in the rate of degradation, underscoring the significance of corrosion in expanding the dispersion of fatigue strength values over time. By integrating the time-dependent nature of corrosion into the fatigue analysis, the t-PSN model provides a more realistic and robust basis for assessing the structural integrity of components exposed to harsh environments. This is particularly crucial for floating offshore wind turbines, where the synergy between mechanical loading cycles and the harsh maritime climate can significantly shorten the expected service life of supporting towers and other critical structures.

2.2 Derivation of Fatigue Stress Spectra

The IEA 15MW reference turbine is selected [6], which is installed on a 150-m-tall tower erected on the UMaine VolturnUS-S floating platform [7]. The diameter of the tower shells varies from 10 m at the bottom to a narrower dimension at the hub, with the thickness ranging from 55 mm at the pile to 44 mm at the transition piece. The design accommodates the dynamic marine conditions and supports the substantial size and forces of the 15MW turbine, ensuring stability and efficiency in offshore environments.

This work assumes the wind speed distribution at the Station CAPE ELIZABETH [9], as shown in Fig. 3. The histogram bars indicate the actual observed frequencies of wind speeds, with a notable peak around the mean wind speed of 6.03 m/s, reflecting the predominant wind conditions recorded at the station, which is located approximately 83.34 km northwest of Aberdeen, Washington. The Weibull distribution, characterized by its red curve, closely matches the empirical data, suggesting that it accurately models the wind speed distribution for this offshore location.

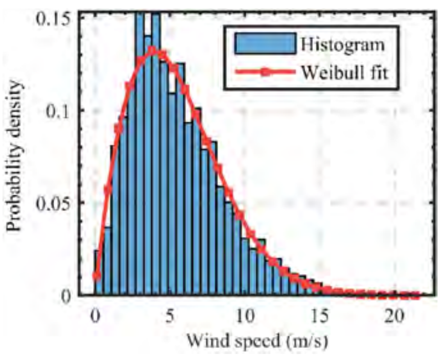

Fig. 3. Wind speed distribution and fitting.

Figure 4 shows the correlation between the wind speed and wave height at the selected station. The data suggest a trend where wave height increases with wind speed, reflecting the energy transfer from wind to water surface. However, the spread of points indicates variability, with some higher wind speeds not resulting in proportionally higher waves, likely due to the complex dynamics of local meteorological conditions. This correlation is crucial for understanding the environmental loading on offshore structures, such as wind turbines, where both wind and wave forces critically influence design and operation. For simplification purposes, a deterministic curve has been fitted from the data to illustrate the correlation between the wind speed and wave height.

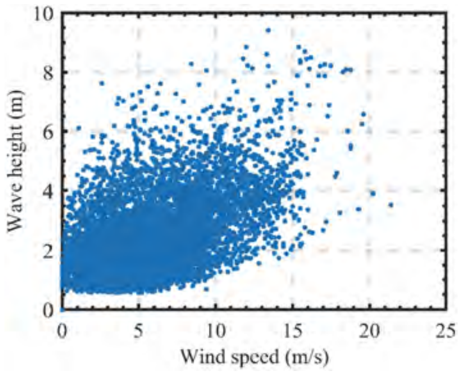

Fig. 4. Correlation between wind and wave.

Based on the wind-wave data, the multi-physics simulation has been applied to derive the fatigue stress spectra at the critical bolt, as illustrated in Fig. 5. Commencing with the synthesis of wind conditions through a wind rose, which quantifies the probabilistic wind speed distribution and directional prevalence, the process advances to the application of OpenFAST [10], a sophisticated simulation tool that models the dynamic interplay between wind forces and the mechanical and control systems.

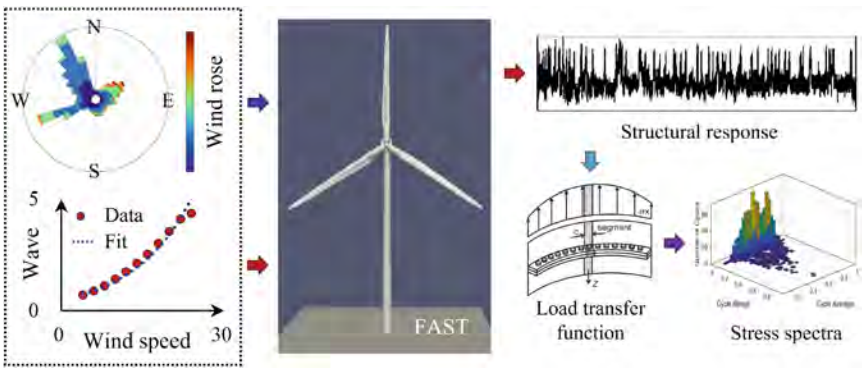

Fig. 5. Derivation of fatigue stress spectra by multi-physics simulations.

Following this, a load transfer function [11] (*e.g.,* Schmidt and Neuper approach) is applied, effectively mapping the complex dynamic responses to the corresponding structural loads. These loads are then translated into stress spectra, providing a comprehensive profile of the cyclic stresses experienced by each turbine segment, and moreover, by the critical bolt.

In this study, the fatigue strength of bolts is treated as a random variable to account the prominent uncertainties in fatigue. It is assumed to follow a log-normal distribution with a mean value of 54.88 MPa and a coefficient of variation of 0.15.

2.3 Probabilistic Deterioration Prognosis

Figure 6 provides a quantitative depiction of the reliability index [12] over the service life of the critical bolt subjected to corrosion fatigue deterioration. Initially, the reliability index starts at a higher value, indicating a low probability of failure. As the service life progresses, the index exhibits a monotonic decrease, reflecting the cumulative damage from corrosion fatigue and the consequent increase in the probability of failure. The marked threshold at an index value of 1.7 corresponds to a service life of approximately 13.6 years, beyond which the reliability falls below the acceptable limit. This inflection point serves as a critical juncture for maintenance or replacement decisions, emphasizing the need for diligent monitoring and proactive intervention to sustain the structural integrity of the bolt within the operational lifespan of the wind turbine system.

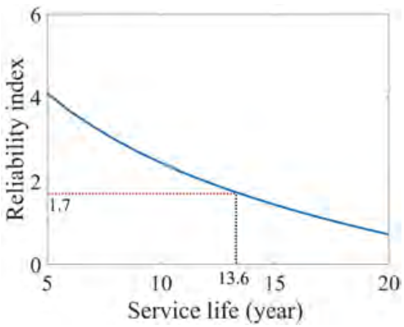

Fig. 6. Time-variant reliability of the critical bolt.

3 Adaptation of Controlling Strategies

3.1 Variation in Controlling Strategies

Three distinct control strategies have been considered in the work, i.e., C0 (the benchmark), C1 (early rated and early cut-off), and C2 (late cut-in, early rated and early cut-off). Figure 7 depicts the three strategies, each defined by their operational parameters at key wind velocities: cut-in, rated, and cut-off. More details can be found in Table 1. Strategy C0 has a cut-in wind speed of 3 m/s, at which point the turbine begins to generate power, a rated speed of 10.59 rpm corresponding to its rated power of 15 MW at a wind speed of 25 m/s, beyond which the cut-off speed is reached, and power generation is halted to prevent damage [6]. In contrast, strategies C1 and C2 share a lower rated rotor speed of 7 rpm, resulting in a rated power of 13.8 MW but differ in their cut-in speeds; C1 commences power production at a wind speed of 3 m/s, whereas C2 waits until the wind reaches 5 m/s. Both C1 and C2 have a cut-off wind speed of 20 m/s. The pitch angle behavior for each strategy varies accordingly [13]; C0 maintains a steady increase in pitch angle with wind speed, C1 exhibits a steeper ascent post-cut-in before leveling off near the rated wind speed, and C2 remains flat until its higher cut-in speed is achieved, then follows a similar trend to C1. These control strategies reflect trade-offs between energy capture efficiency and structural load management, with each approach offering distinct benefits and limitations depending on the wind speed profile and desired turbine performance characteristics.

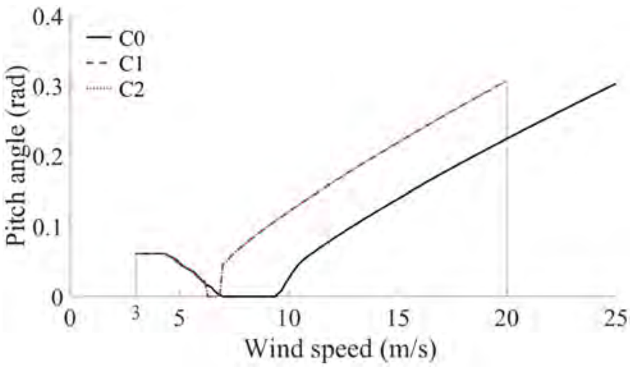

Fig. 7. Different types of controlling strategies.

Table 1. Different controlling strategies and parameters.

Strategy	Wind velocity (m/s)			Rated rotor speed (rpm)	Rated power (MW)
	Cut-in	Rated	Cut-off		
C0	3	10.59	25	7.6	15
C1	3	7	20	7	13.8
C2	5	7	20	7	13.8

3.2 Results and Discussion

Figure 8 presents the reliability evolution of the critical bolt under the two different control strategies, C1 and C2. Recalling benchmark scenario (Fig. 6), the reliability index of the bolt decreases uniformly with time, reaching the threshold value of 1.7 at approximately 13.6 years, indicating the point at which the bolt's reliability is compromised.

Comparatively, Fig. 8a, representing Strategy C1, shows a similar downward trajectory but with a slightly higher reliability threshold of 1.72, reached just beyond the 20-year mark. Strategy C2, depicted in Fig. 8b, exhibits a near-identical pattern to Strategy C1, with the reliability index threshold marginally higher at 1.73, also surpassed just after 20 years. Both strategies demonstrate an improvement in the bolt's reliability over the benchmark, albeit marginally, suggesting that these control strategies may extend the service life of critical components. The comparison elucidates that while Strategies C1 and C2 offer a slightly extended service life over the benchmark, the differences are minimal, indicating that further optimization of control strategies may be necessary to achieve a more substantial increase in component longevity. This underscores the importance of refining control strategies to enhance the reliability and hence the service life of critical turbine components under the persistent challenge of corrosion fatigue.

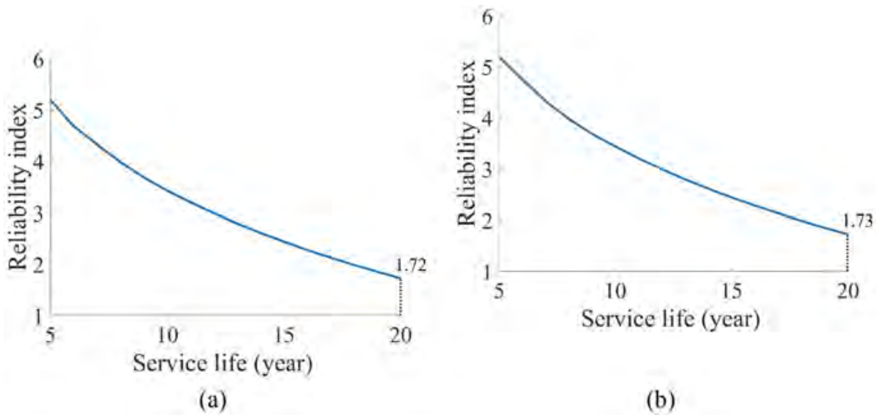

Fig. 8. Influence of different strategies on the reliability evolution of the critical bolt: (a) Strategy C1; (a) Strategy C2.

Table 2 provides a comparative analysis of power generation under the three wind turbine control strategies, in terms of the consequent annual power generation. Strategy C0 yields the highest annual power generation of 56,502 MWh. This strategy takes full advantage of the lower wind speeds for power generation, which corresponds to a more aggressive energy capture approach but may contribute to a faster deterioration in the reliability index of critical components, as suggested by the lower reliability threshold of 1.7 reached after 13.6 years (Fig. 6).

In contrast, Strategy C1, with identical cut-in and higher cut-off wind speeds as compared to C0 but a lower rated rotor speed of 7 rpm, generates less annual power, 51,142 MWh. Strategy C2 is more conservative with a higher cut-in wind speed of 5 m/s, the same rated rotor speed, and cut-off wind speed as C1, leading to the lowest power generation of 45,073 MWh. Both C1 and C2 exhibit slightly higher reliability thresholds of 1.72 and 1.73, respectively, surpassing the benchmark after 20 years (Fig. 8), suggesting that these strategies may be more conducive to preserving the structural integrity of the critical bolt over time. When correlating power generation with the reliability indices, it's evident that more conservative controlling strategies - C1 and C2 - while producing

Table 2. Power generation under different controlling strategies.

Strategy	Wind velocity (m/s)			Annual power generation (MWh)
	Cut-in	Rated	Cut-off	
C0	3	10.59	25	42,102
C1	3	7	20	39,520
C2	5	7	20	35,271

less energy annually, potentially extend the service life of critical components, offering a trade-off between immediate energy yield and long-term structural reliability. This analysis highlights the strategic decisions to be made between operational efficiency and durability in wind turbine management.

4 Conclusions

Based on the major findings in the present study, the following conclusion can be drawn.

- The choice of control strategies has a profound effect on the rate of corrosion fatigue in FOWT supporting structures, with direct implications for the service life of critical connections.
- While Strategy C0 (the original benchmark) maximizes power generation, it detrimentally impacts bolt reliability, hastening the approach to critical reliability thresholds. Alternatively, Strategies C1 and C2, through conservative operational limits, effectively prolong the structural integrity of bolt connections, suggesting a strategic prioritization of long-term durability over immediate power maximization.
- The work also highlights the necessity to integrate control strategy with real-time structural health monitoring and to leverage advancements in material science to fortify the FOWTs against the harsh marine environment.
- Future works are suggested to explore next-generation predictive operation and maintenance protocols, like digital twins, to further the operational efficacy and durability of FOWTs.

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Wind Aerodynamics and Related Energy Potential of Urban High-Rise Vertical Farms

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Abstract. This paper presents the development of a benchmark vertical farm that could potentially enable the sustainable development of urban and rural areas. The investigation seeks to tackle global issues linked to sustainability development goals such as zero hunger, affordable clean energy, industry innovation and infrastructure, amongst others. Vertical farms enable plant-friendly environments in urban skyscrapers through agricultural techniques, often identified as consuming large amounts of energy. These facilities could be fully embedded into urban planning as clean energy sources such as solar and wind are fully utilised. This paper scrutinises the potential for wind energy utilisation in a vertical farm with different planting corridor widths. The study also seeks to clarify the potential for energy harvesting by identifying suitable micro wind turbines installed in the façade and roof. The vertical farm prototype is elliptical and has a total height of 108 m, 80 m width, and 60 m chord. This paper studied the prototype with corridor widths of 3 m, 4 m, 5 m, and 6 m, respectively. The maximum inlet wind speed was defined as 20 m/s, and the atmospheric boundary layer condition was applied to simulate an urban wind environment and observe the aerodynamics of the farm. The results showed that the benchmark building with a corridor of 5m-width has the best potential for wind energy harvesting, particularly when the wind turbines are located on the roof.

Keywords: Vertical farm · CFD · Wind energy harvesting · Urban planning

1 Introduction

As populations continue migrating to cities, energy, food, and transportation demand increases. Thus, the growing energy crisis has become a top priority concern for the government. As early as 1999, Dr. Dickson Despommier proposed the concept of urban vertical farms [1], and since then, many countries have gradually accelerated their integration into urban construction. According to past studies [2–4], multi-layered crop-growing platforms are used in the innovative agricultural practice known as vertical farming. This has drawn interest, due to its potential to boost crop yields per unit amount of land [5, 6], especially compared to conventional agriculture and greenhouses. Urbanisation and population growth are driving the global vertical farming market, which,

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in one case study, reached $5.6 billion in 2022 and is expected to exceed $35 billion by 2032 [7]. There are precedents for the ability of vertical farms established in cities to provide fruits, vegetables, and sideline products. However, there are fewer studies to confirm the wind energy potential of vertical farms. The dense arrangement and staggered distribution of building complexes lead to complicated urban turbulence and variable wind trajectories. It has been demonstrated that urban high-rise buildings have considerable potential for wind energy [8–10], especially for ultra-high-rise buildings over 100 m subject to high winds. However, vertical farms consume more energy than conventional field agriculture, greenhouses, and traditional commercial and residential buildings [11]. If a tall vertical farm can efficiently harvest wind energy, it could provide power for agricultural production and reduce energy loss in power transmission.

To assess the energy generation capacity of the benchmark building, we determined the wind penetration capacity of the corridor considering various widths. Simultaneously, since urban complexes have shown advantages for wind energy harvesting and transformation [12, 13], we appended a horizontal axis wind turbine (HAWT) and a vertical axis wind turbines (VAWT) on the façade and roof. The results obtained that, although the VWAT can collect wind from all wind directions, it is not as adaptable as the HWAT regarding the degree of application and energy conversion efficiency. Therefore, the HWAT is the primary type of wind turbine installed in nominal urban buildings. Furthermore, there are two main types of configurations for installing wind turbines in buildings [14]. One is the Building Mounted Wind Turbines or top-mounted wind turbines, which are located on the roof as an additional structure and are suitable for building structures of any shape. The other is building augmented wind turbines, generally installed on building façades and mounted on outward-facing extended towers. Thus, this study compares the running effects of the wind turbine placed on the surface and the roof of the vertical farm.

2 Methodology

2.1 Computational Model

The widely recognised Computational Fluid Dynamics (CFD) simulation software ANSYS Fluent is applied to calculate complex buildings' wind traces, velocity distributions, pressures, and wind speed vectors. The design flow is shown in Fig. 1. The numerical simulation method can recreate the atmospheric boundary conditions by setting adequate boundary conditions, turbulence, inlet velocity, and other environmental parameters.

Fig. 1. Design flow of CFD simulation.

The CFD testing model is shown in Fig. 2. The height of each floor is 5.6 m, which can accommodate indoor planting shelves and supplemental light. The model has an ellipsoid geometry with the assemble of 20 stories, giving a total height (H) of 108 m, width (W) of 80 m, and chord (B) of 60 m. The computational domain (Fig. 2b) has a height of 6H, width of 10H + W, and length of 20H + B [15, 16]. Thus, the blocking rate in the computational domain is guaranteed to be less than 3 per cent [17, 18].

To study the wind energy potential and applications of urban high-rise vertical farms, we varied the width of outdoor corridors. This space thus became an independent variable in the concept design, taking values of 3 m, 4 m, 5 m, and 6 m. Furthermore, the wind harvesting potential of the facility is bounded by an inlet maximum velocity of 20 m/s.

The location of the different arrangements of wind turbines is shown in Fig. 3. Turbine 1 has a blade diameter of 15 m, with an extended tower height of 3 m and a hub centre height of up to 86.4 m. Turbine 2 has a blade diameter of 15 m, a tubular tower height of 20 m, and a hub centre height of up to 128 m.

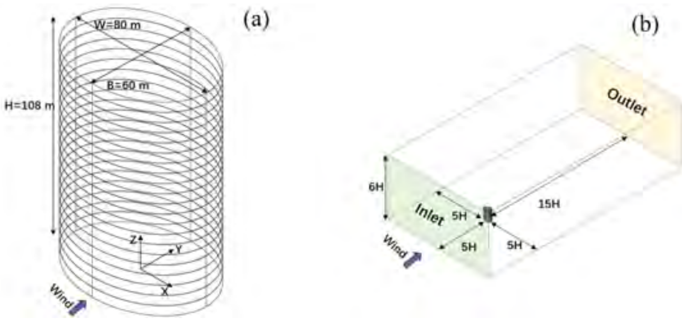

Fig. 2. Schematic diagram of (a) CFD model and (b) computational domain.

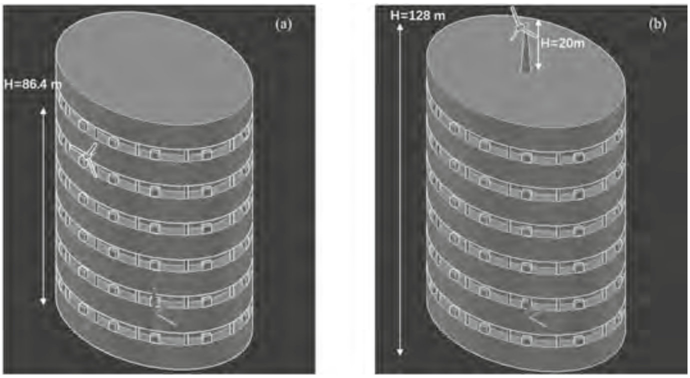

Fig. 3. Arrangement of (a) Turbine 1 and (b) Turbine 2.

2.2 Meshing and Boundary Conditions

Coarse, base, and fine grid sizes were selected for the meshing independence test. The elements of the three grids are 1309804, 3298962, and 7404185, respectively. The results showed that for the average pressure values within the same reference area, the ratio of the difference between the values of the base grid and the other two grids is 1.3% and 0.2%, and the inaccuracy is within normal limits. Therefore, the base grid was sufficient to meet the design requirements.

The $k - \omega$ turbulence function simulates the turbulence in the atmospheric boundary layer. When defining the pressure outlet boundary condition, the pressure of the fluid with the pressure at the flow outlet should be equalised, i.e., P = 0, where P denotes the pressure of the fluid at the outlet [19]. This boundary condition aims to enable the fluid flow at the flow outlet to satisfy the principle of conservation of mass and to ensure the accuracy and stability of the calculation results. The walls of the computational basins were calculated with symmetrical wall conditions with no slip. The solution is performed by the method of COUPLE, which allows the results to converge more quickly, 10^{-4} is taken as the convergence criterion.

2.3 Validation

To verify the validity of this simulation test, the surface wind pressure coefficients of the benchmark (with 5-m width) were determined, as well as the wind speeds at different heights in the basin. The comparison between the wind speeds of different heights in the basin calculated according to the mean wind speed profile and the CFD is shown in Fig. 4a. The numerical results are in good agreement with theoretical values.

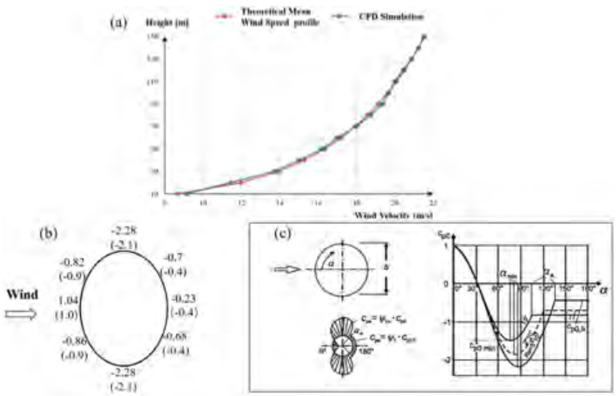

Fig. 4. (a) Theoretical and simulation wind speed in different heights of IV Terrain Category, (b) Mean wind coefficients for the vertical farm benchmark, (c) Recommended external coefficients for circular cylinders.

*The values in the brackets in Fig. 4b are resulted from Fig. 4c, and Fig. 4c is from BS EN 1991-1-4:2005 + A1:2010 - Wind actions [20].

Meanwhile, Fig. 4b shows the wind pressure coefficient values on the surface of the benchmark, which compare with those recommended by the norm BS EN 1991-1-4 for circular cylinders. This mapping was deemed necessary as neither experimental evidence of the prototype nor code recommendations for its shape and aspect ratio are currently available. Yet the comparison results are satisfactory, as presented in Fig. 4b and 4c.

3 Results

3.1 Impact of Wind Turbulence

Figure 5 shows the wind flowing past the surface of the building. We observe that the velocity on the vertical and horizontal planes located 3 m away from the windward façade and 15 m above the roof did not decrease due to the roughness of the façade. The magnitude of the value is comparable to the wind speed of the bypassing flow around the building. This indicates that the wind turbulence generated on facades mitigates at a certain distance from the farm's surface. Therefore, wind turbines could be installed with the rotating blades protruding to avoid the turbulent boundary layer around the building envelope to maximise the performance of the wind turbines.

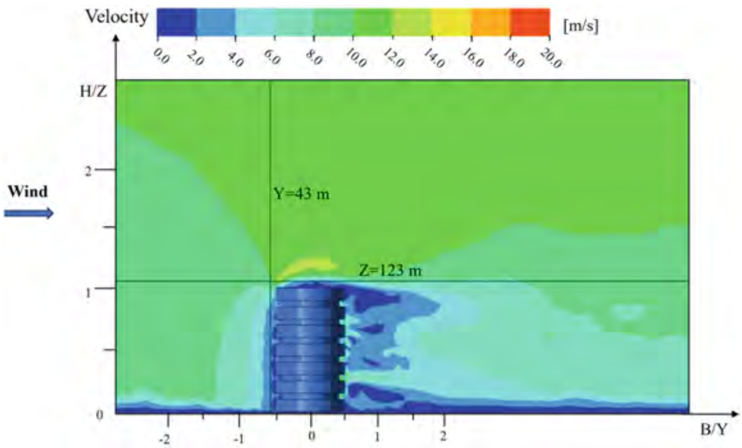

Fig. 5. Diagram of velocity distribution around the vertical farm.

3.2 Impact of Corridor Width

Four separate tests were designed to investigate the influences of corridor width on wind energy harvesting. Figure 6 shows the results of the simulations via velocity vector plots in the XY plane of the models developed with the four ventilated corridor widths. Model (c) yields the most significant values of velocity and pressure in the domain. The largest wind speed reaches a value of 19.8629 m/s at both sides of the opening of the corridor, which translates into a peak wind pressure coefficient that occurs at the windward side of the building. In contrast, the lowest pressure coefficient occurs on the leeward side of it. These results show that the width of the planting corridors with openings affects the wind pressure distribution, which in turn impacts the energy harvesting of the vertical farm. Considering the wind energy side of the investigation, the 5m-wide outdoor ventilation corridor was selected as the best for energy efficiency and building sustainability.

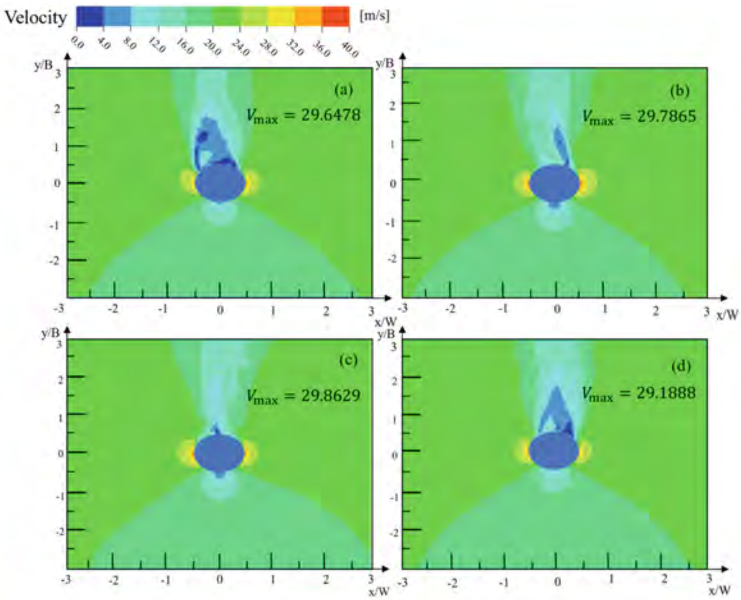

Fig. 6. Diagram of velocity plots in $H = 86.4$ of (a) 3-m width, (b) 4-m width, (c) 5-m width, and (d) 6-m width corridor in the vertical farm.

3.3 Impact of the Location of the Wind Turbines

The results of the wind flow streamline around the wind turbine are shown in Fig. 7, with Fig. 7a and 7b presenting the velocity vector diagram in the YZ plane. There is no backflow generated at the outlet. As the wind flows across the surface of the building, the wind speed decreases due to the blocking effect induced by the building's appearance; the more the wind approaches the surface of the building, the lower its velocity. The wind turbines (named Turbine 1 and Turbine 2, respectively) were placed on the windward side of the building at $H = 86.4$ m which lies 3 m apart from the building façade, and on the roof, the rotating centre is at $H = 128$ m. The Turbine 1, surrounded by a winding flow, was exposed to an average velocity of 8.7 m/s, whereas Turbine 2 was exposed to 11.2 m/s when the inlet velocity is at its limiting value of 10 m/s. This means the wind turbine has a good potential for generating electricity and can avoid the effects of turbulence caused by the vertical farm building. A certain rotational speed can be maintained at this speed to achieve uninterrupted power generation. The average value of the wind pressure coefficient is about 40.4% greater than that of Turbine 2, which means that rooftops on the vertical farm have more potential for wind energy harvesting.

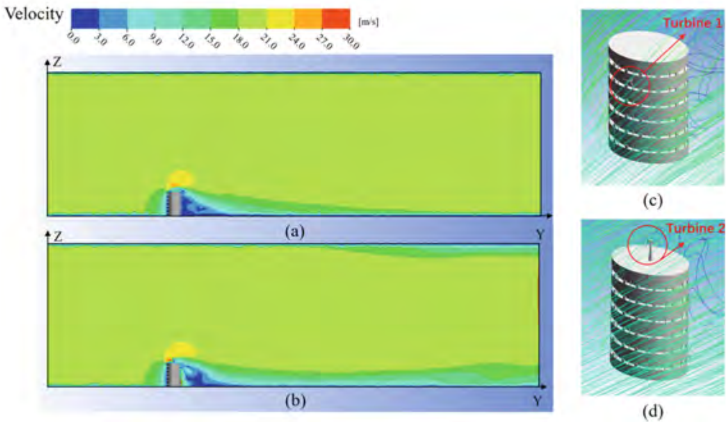

Fig. 7. Velocity and streamline plots of the vertical farm. (a) Contour of velocity plots with Turbine 1, (b) Contour of velocity plots with Turbine 2, (c) Streamline in vertical farm with Turbine 1, and (d) Streamline in vertical farm with Turbine 2.

The potential wind energy of the wind turbine can be calculated from the wind energy formula (Eq. (1)). According to Betz's Law, an ideal wind turbine's maximum wind energy utilisation factor is 0.593. Meanwhile, to compare the leading wind energy captured by wind turbines under different inlet wind speed conditions, the electricity produced by each revolution of Turbine 1 and 2 in different inlet velocities is shown in Fig. 8.

$$E = \frac{0.5 * \rho * A * V^3 * \eta}{3.6 * 10^6} \tag{1}$$

where E denotes the wind energy per unit time (KW·h), p denotes the air density (Kg/m^3), A denotes the effective area of the wind turbine blades (m^2), V denotes the wind speed (m/s), and η denotes the wind energy conversion efficiency.

In summary, the wind turbines' electricity grows as the inlet wind velocity increases. Still, this trend does not go on forever, eventually reaching a peak and stabilising. Meanwhile, the amount of electricity the wind turbine generates varies depending on the location. The comparison of Turbines 1 and 2 shows that the roof of the vertical farm has a better ability to capture wind due to its high ventilation and air flow rate.

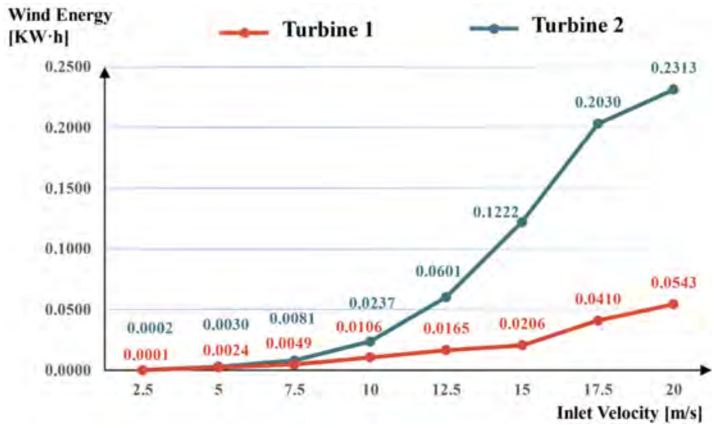

Fig. 8. The electricity of one revolution of Turbine 1 and 2 in different inlet velocities.

4 Conclusion

The evidence provided in the paper allows us to conclude that the vertical farm prototype has potential for wind energy harvesting, showing sound aerodynamic performance. When the wind crosses the ventilation corridor, the airflow is compressed, and the wind speed is enhanced, especially for a corridor of 5-m width. Simultaneously, the results showed that the average wind speed around the blades on the turbine placed on the roof is higher than on the building façade, hence more efficient for generating energy. The electricity produced by each revolution of Turbine 1 and 2 in inlet velocity of 10 m/s is 0.0237 KWh and 0.0106 KWh, respectively. Thus, rooftop wind turbines in the vertical farm have better potential for capturing wind energy.

This paper is based on the results obtained from the previous literature review and CFD simulation tests; the drawback of this study is that there is no experimental demonstration, and the conclusions obtained are simulation results. Future research will use wind tunnel tests to verify the accuracy of the experimental results. The full results are in ongoing calculation procedures through wind tunnel tests.

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Design of Photovoltaic/Thermal Collectors with Thermal Storage and Batteries to Enhance Building Performance and Resilience in Cold Climate

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Abstract. This study consists of a sensitivity analysis of photovoltaic/thermal (PV/T) collectors, liquid thermal storage, and battery systems applied for the offices of a school building near Montreal, Canada to enhance building performance and resiliency to power outages during winter operation. The analysis was applied for 3 days in January with mixed solar conditions by varying the sizing of each of the components to achieve at least 8 h of self-sufficiency, the average length of power outages. It was found the optimal sizing for the studied system, while minimizing component costs, is to dimensions PV/T collectors to meet the base heating load, while maximizing thermal storage, and diminishing battery capacity to meet the base heat pump electricity consumption. For the case study, the optimal configuration was 27 PV/T, a 908 L thermal storage tank, and 10 kWh of battery capacity, to consistently achieve over 8 h of self-sufficiency in mixed sunny and cloudy winter conditions.

Keywords: Photovoltaic/Thermal · Thermal Storage · Battery · System Sizing · Cold Climate · Resilience

1 Introduction

Solar energy is the most accessible decentralized energy source to enhance building power generation and reduce carbon emissions. Hybrid photovoltaic/thermal (PV/T) collectors have significant advantages compared to typical photovoltaic (PV) panels and thermal collectors by combining their power generation for the same surface area. PV/T uses a heat exchanger to capture the solar energy not converted into electricity from the PV cells. In this way, PV/T can achieve significantly greater efficiencies near 80% total efficiency depending on designs [1]. The added thermal energy generation is especially beneficial for buildings that are in heating-dominant climates such as in Canada.

Building-integrated energy generation can significantly reduce the building's net energy consumption as well as increase the building's resiliency. The potential for self-generation reduces dependency to utilities and, when combined with energy storage,

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can enable buildings to significantly reduce power outages. However, solar energy intermittent and unpredictable nature can make the design of these systems to meet building energy demands complex. In this way, multiple studies have evaluated the ideal sizing of battery storage systems to enhance renewable energy generation [2]. Intuitive methodologies are often utilized to approximately size PV systems based on the monthly solar energy, while other studies favor artificial intelligence methodologies to find an appropriate solution without guaranteeing perfect sizing [3]. Mathematical programming models are also utilized to find optimal PV-battery sizing for their applied case study building [5].

Similarly, thermal storage solutions for solar thermal systems have also been studied broadly [6]. Water thermal storages are often used for solar applications since they are an effective and affordable solution achieving good performance for low-temperature applications [7], such as building heating. Thermal storage adequate sizing has shown that it can significantly improve solar thermal collector performance [8], with tank stratification improving the efficiency [9]. Studies have also investigated the ideal sizing for PV/T collectors to maximize their performance [15], however thermal storage sizing remains the most common difficulty of PV/T system implementation [12].

Solar-energy storage systems' appropriate sizing can enhance building performance as well as increase building resiliency by mitigating power outages. In the United States, electricity consumers averaged 7 h of power interruption in 2021, with power outages from major events going as high as 8 h on average in recent years [13]. Some studies have investigated the potential of PV-battery systems to minimize these power outages by utilizing optimal sizing for the designed systems [14] as well as developing stochastic methods to incorporate solar variability to maximize resiliency [15]. In this way, PV/T combined with batteries and thermal storage has the potential to enhance typical PV-battery systems for building performance as well as resiliency to power outages.

The aim of this study is the optimization of PV/T collector, batteries, and thermal storage sizing through a sensitivity analysis to maximize system performance as well as increase building resiliency to power outages for cold climate building heating.

2 Methodology

This study consists of a sensitivity analysis to optimize the sizing of a PV/T-battery-thermal storage system applied as a case study on the offices of a school building in Sainte-Marthe-sur-le-Lac, near Montreal, Canada. The system is optimized to increase building resiliency to power outages for a minimum of 8 h of self-sufficiency. The self-sufficiency duration is calculated based on the duration where the stored total energy can meet the totality of the load starting when the PV/T electrical generation cannot meet the entirety of the load. The studied system is to be dimensioned to meet the heating load of the school offices' radiant hydronic loop during winter operation. The initial system dimensions are based on an existing operational retrofitted PV/T-thermal storage system on a research building. The studied system components are modeled with Python (Fig. 1).

Fig. 1. Studied school building, Horizon-du-Lac (near Montreal, Canada) [16].

The school building is located near Montreal, Canada with a back façade facing 37° South-East where the PV/T collectors would be installed in the façade at a 90° slope to maximize solar gains for winter operation. The solar radiation, ambient temperature, wind speed, and direction, weather data for the school location were taken from Solcast database at the school coordinate [14] and are utilized by the model. The performance of the system is evaluated for 3 days in January with mixed conditions, a sunny day, and 2 partly sunny/cloudy days with exterior temperature varying from −20 °C to 0 °C with an average 10 °C temperature (Fig. 2).

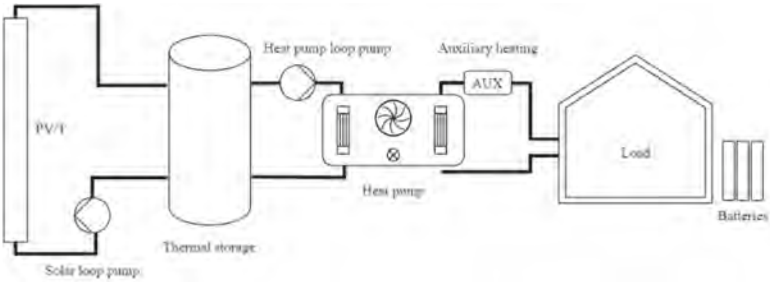

Fig. 2. PV/T-battery-thermal storage system configuration.

The building loads are taken from historical 2020 measured data of the radiant slab floor heating of 5 offices in the school with a total floor area of approximately 144 m^2. The average daily heating load of the offices during January and February was 81 kWh (0.5625 kWh/m^2) and the average peak load was 7.5 kW. The studied system consists of liquid-based PV/T collectors with parallel thermal hydronic connections that directly feed a large liquid thermal storage tank. The PV/T and storage tank have a mixture of 50/50 glycol water to minimize freezing. The tank is connected to a heat pump that heat radiant slabs in the school offices. An auxiliary heating source is used if the tank-stored heat is insufficient. The PV/T electrical generation can be used directly to power auxiliary heating, charge the battery, or sent to the grid. It is assumed that the excess electrical generation cannot be used for other building loads to recreate a self-reliant building.

The PV/T collector panels, the tank dimension, and the battery maximal capacity are varied with the sensitivity analysis as shown in Table 1 to evaluate the impact on the building load and the PV/T performance. The PV/T and thermal storage costs are based on the component cost of an existing system in Quebec, Canada, while the battery costs are based on the commonly used residential Tesla PowerWall.

Table 1. Sensitivity analysis evaluated varied parameters and costs

Components	Varied parameters	Component cost
Quantity of PV/T	[18, 27, 36, 45, 54] (1.6 m^2/each)	456$/each
Thermal storage volume	[454, 908, 1 362, 1 816, 2 270, 2 725] (L)	2.64$/L
Battery capacity	[10, 20, 30, 40, 50, 60, 70] (kWh)	554$/kWh [17]

2.1 PV/T Collector

The PV/T collectors are modelled with a grey-box 1st-order thermal network approach that was developed for control application in a previous study and experimentally validated with a less than 5% error [18]. The model is calibrated utilizing experimental data to improve its accuracy for real-world operation. The electrical model of the PV/T is based on the manufacturer's performance specifications and the PV cell temperature that is calibrated with a set coefficient of $\alpha_{corr} = 0.86$ based on experimental measurements. The thermal model is based on energy balance equations of each of the thermal nodes of the thermal network of Fig. 3 with an effective capacitance located at the thermal heat exchanger.

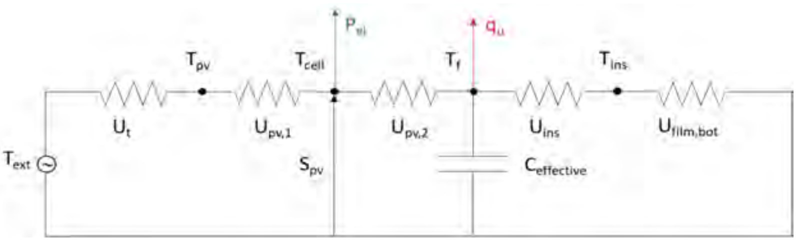

Fig. 3. PV/T thermal network [18].

The calibration is based on a single day of data from real-world operation from identical PV/T collectors installed on the façade of an institutional building in Quebec. The quantity of PV/T collected is evaluated in this study from 18 panels up to 54. It is assumed that the hydronic circuits of the collectors are connected in parallel. The solar PV/T control pumps are set to operate when the temperature of the tank top node is below 1.5 °C the temperature of the PV/T outlet fluid temperature and stop when the difference is below 0.5 °C. The pump flow rate is based on the quantity of PV/T collectors set at 100 kg/h per panel based on the manufacturer's recommendations.

2.2 Thermal Storage

The thermal storage tank is directly connected to the PV/T hydronic thermal loop and is filled with a 50/50 glycol-water mix. The tank is modelled with 5 control volumes to evaluate the stratification between the different tank layers. Since the flow rate is dependent on the number of solar collectors, depending on the studied configuration stratification could be minimal or have a large impact on performance. The tank heat loss coefficient was calibrated utilizing experimental measurements to 3.25 W/m^2-K. The tank nodes are modelled with energy balance equations from Klein and al [19].

$$C_i \frac{dT_i}{dt} = \dot{m}_1 c_p (T_{i-1} - T_i) - \dot{m}_2 c_p (T_{i+1} - T_i) + U_i A_i (T_{amb} - T_i) \tag{1}$$

where C is the thermal capacitance, $\dot{m}_1$ and $\dot{m}_2$ are the source/load mass flowrate, U is the heat loss coefficient, c_p is the specific heat, T_{i-1}, T_i, T_{i+1} are the above, current, and below control volume source/load temperature, and T_{amb} is the ambient temperature.

2.3 Heat Pump

The heat generated during the winter months for unglazed PV/T collectors can be significantly affected by the exterior temperature and wind speed causing significant thermal losses. The heat quality is significantly affected which often necessitates a heat pump to increase the temperature for building heating purposes. In this way, a heat pump was selected from Nordic GHP which has a large high-temperature range that is suitable for winter solar applications. The selected heat pump can operate between tank temperatures from 7 °C to 32 °C with an output temperature of at least 47 °C, ideal for radiant floor heating. Experimental measurements have shown that an 18 PV/T configuration with a 454 L thermal storage tank could achieve a maximal temperature of up to 31 °C during winter operation – which is ideal for the selected heat pump. The heat pump model is based on performance curves from the manufacturer's available data [20] where the COP is the coefficient of performance.

$$\mathrm{COP} = 0.12578 * \mathrm{T_{ELT}} + 0.91531 \tag{2}$$

The controls for heating the school offices are rule-based, where the heat pump is used for heating if the temperature of the tank is greater than 10 °C and the PV/T electrical generation with the auxiliary heating is not enough to meet the load. The heat pump operation stops if the tank temperature in the tank reaches 7.5 °C.

2.4 Battery

The batteries are utilized to store the excess electrical energy generated by the PV/T collectors. The stored energy is then utilized to meet the electrical load that is not met by the heat pump, including the heat pump's electricity consumption, to reduce the heating load until it reaches zero. The battery's State-of-Charge (SoC) is based on the electrical load provided by the PV/T and the discharge to meet the office's heating load. The SoC is limited to a range of 20 to 80% to minimize the battery degradation effects by operating in a linear portion of the nominal discharge curve [21]. In this way, the battery SoC was modelled based on the battery's maximal capacity C_{bat}, the time Δt, and the charge/discharge power rate $P(t)$ that was limited to a C-rate of 0.5 to minimize long-term battery degradation.

$$SoC(t) = SoC(t-1) + \frac{P(t) * \Delta t}{C_{bat}} \tag{3}$$

3 Results

The three studied parameters were varied in a sensitivity analysis to determine their impact on the performance of the system to maximize the number of hours the system can be self-sufficient after a fully sunny day in winter. The largest difference in system performance is caused by the variation in the number of PV/T collectors and the thermal storage tank, which directly affect the potential heat gains. Figure 4 shows the number of self-sufficient hours with a fixed battery capacity of 10 kWh and variations of PV/T collectors and tank volume. There is significantly reduced performance at 18 PV/T compared to other configurations. Increasing the tank storage does improve its performance at a tank volume of 908 L with a decrease in performance when it further increases. Larger tanks have higher stratification and lower temperatures, improving collector efficiency.

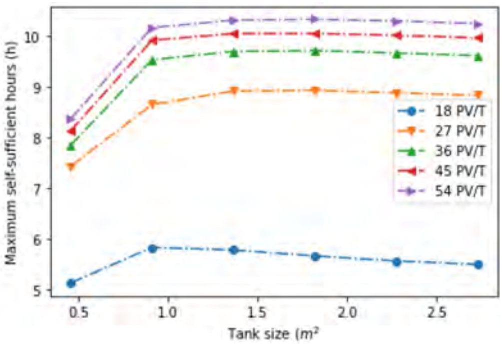

Fig. 4. Maximum self-sufficient hours based on PV/T quantity and tank size with a fixed 10 kWh battery capacity.

However, when the tank volume is too large for the generated collectors' thermal energy, the temperature quality is too poor to be utilized by the heat pump. At 27 panels and larger, there are significant performance gains, but the number of self-sufficient hours is mostly below 8 h without increasing tank size, significantly improving performance up to 1362 L. Similarly, if we observe the impact of varying the thermal storage and battery size with a fixed number of PV/T collectors, we have a significant difference in performance.

Figure 5a shows these effects with a 27 PV/T configuration. The increase in battery capacity significantly improves the number of self-sufficient hours until it is maximized at 30 kWh and there is not enough excess PV electricity generated to charge the battery.

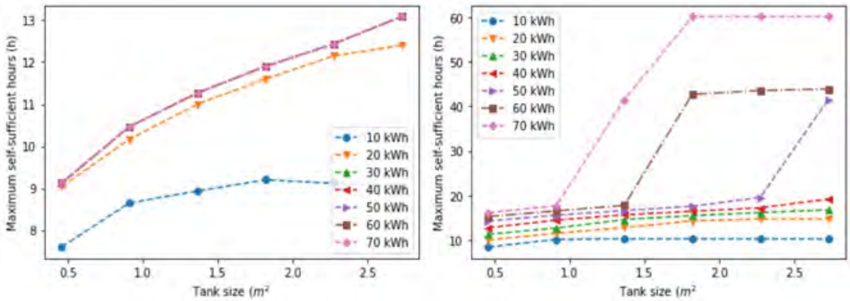

Fig. 5. Maximum self-sufficient hours based on tank size and battery capacity. 5a (Left); For 27 PV/T collectors. 5b (Right); For 54 PV/T collectors

However, if we have 54 PV/T collectors (Fig. 5b), there are important increase in the number of hours from the greater storage capacity since the system can better utilize the excess generated electricity, improving self-sufficiency until the next day's sunny conditions – significantly inflating results. Additionally, increasing the storage tank volume seems to also significantly improve the hours of self-sufficiency when the battery capacity size is large enough to meet the heat pump electrical generation, which seems sufficient near 20 to 30 kWh with 36 panels. Figures 6a and 6b, respectively shows the effects of the variation of the three parameters on the number of self-sufficient hours and the component costs.

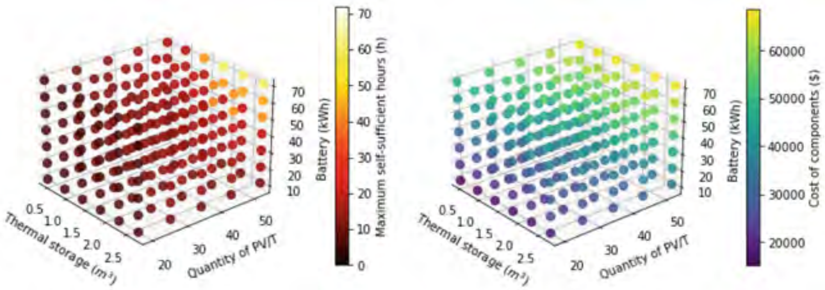

Fig. 6. Thermal storage, PV/T quantity, and battery capacity effects on: 6a (Left); the maximum self-sufficiency. 6b (Right); the component cost.

In Fig. 6a, we can observe that the increase in battery capacity has the largest impact on the system's self-sufficient hours, with thermal storage being the smallest. Nonetheless, the thermal storage sizing has a larger impact when there is enough PV/T collector for the studied case study load, necessitating at least 27 collectors. However, the effect of the components cost is the opposite, as seen in Fig. 6b. Although batteries are necessary to maximize self-sufficient hours, they increase significantly the cost compared to tank volume. In this way, the best configuration to maximize the number of self-sufficient hours for the lowest cost would have to utilize enough PV/T collectors to just meet the heating load, maximize the thermal storage tank, and reduce the battery capacity to meet the heat pump's electrical consumption. For example, a 1st configuration of 27 PV/T, 908L tank, and 10kWh battery would cost 18 861$ and achieve 8.65h of self-sufficiency while a 2nd configuration of 27 PV/T, 454 L tank, and 20 kWh battery would cost 23 856$ with 9.03h of self-sufficiency. The 1st configuration is the optimal low-cost sizing for the studied scenario shown in Fig. 7 to reach 8h of self-sufficiency.

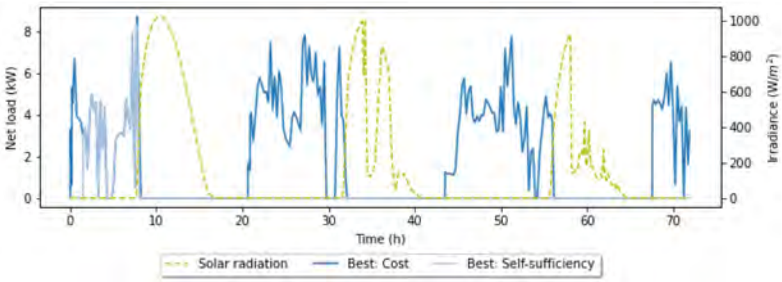

Fig. 7. Net load for 3 days in January for 2 configurations: Minimum cost and most self-sufficient.

However, if the design goal is to achieve more than 1 day of self-sufficiency during a mix of sunny and partly sunny days in winter, the minimum cost configuration that could meet the entirety of the load for 3 days was 54 PV/T, 1816L tank, and 70 kWh battery for a total component cost total of 65 422$ as shown in Fig. 7.

4 Discussion

The sensitivity analysis found that the most important parameter is to size the PV/T collector array to only just meet the base building load and optimize the thermal storage tank dimensions based on the PV/T quantity. Battery capacity should be designed based on the desired application to meet the building and the heat pump load for the required minimum number of self-sufficiency hours. In the case of this study, to minimize power outages reaching 8 h on average at the lowest component cost, 27 PV/T, a 908L tank, and 10 kWh battery capacity were found to be able to reach 8 h for all 3 days of different climatic conditions during winter. Nonetheless, depending on the applications, improving thermal storage to 1816L could slightly improve performance of 33 min, while increasing battery capacity to just 20 kWh would improve 1h 33 of self-sufficiency and both together 2h57. In this way, battery capacity has the largest impact on improving self-sufficiency if there is enough excess electricity produced.

However, these components have different impacts on the system's initial costs, with batteries and PV/T collectors' costs being more substantial than the storage tank. In this way, the final configuration with a cost of 18 861$ would be 19 951 $ with a larger tank of

1816L, 24 401$ with a 20 kWh battery capacity, and 25 491$ with both improvements. Notably, design requirements significantly vary depending on the building, climate, and its application. In this way, for the case study, an appropriate sizing range for the case study during winter operation would be between 27 PV/T collectors (43 m^2), a tank size between 900L to 2000L, and a battery capacity from 10 kWh up to 20 kWh for a building daily load of 81 kWh/day.

The study's main limitations are that the design was only optimized for a short duration in winter conditions without considering the effects of yearly changes in solar radiation and temperature, in addition to assuming the power outages were always after solar energy production in the evening. System design analysis considering a long-term approach for a full year as well as utilizing a smart predictive control methodology with probabilistic models to predict power outage events could improve real-world accuracy and reduce these limitations.

5 Conclusion

This study presented a design sensitivity analysis of a PV/T-battery-thermal storage system implemented in the offices of a school building to determine the optimal sizing to enhance building resiliency to power outages during winter. The optimal sizing to meet the office 81 kWh/day heating load was found to be around 27 PV/T (43 m^2), 908L thermal storage, and 10 kWh battery to minimize cost while being self-sufficient for 8h, the average power outage length from caused external factors. The system's most cost-effective approach to improve performance was found to size the PV/T collectors based on the load without oversizing, maximize thermal storage size, and minimize battery capacity to meet the minimum heat pump electrical consumption. Nonetheless, since the system performance is highly dependent on the building load, the climate, and the system applications. The study identifies key parameters to consider for PV/T with energy storage systems to improve building performance and resiliency for winter operation while reducing component costs.

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Energy Efficiency in the Higher Education Institutions: A Review of Actions and Their Contribution to Sustainable Development

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Abstract. Universities are among the largest public sectors and energy consumers in many countries worldwide. They are considered crucial places to learn about opportunities to adopt sustainable and renewable energy to meet global greenhouse gas emission targets and incentivize economic growth. In this study, different energy efficiency strategies on university campuses were analyzed to investigate the level of engagement in practical actions at universities and the reduction of the environmental impacts of this sector. The results show that energy actions on university campuses are fewer and focused on plans for renewing energy systems and reducing energy consumption in buildings. Only a small portion of universities' energy consumption comes from renewable sources. There is a need for more empirical studies on the description of actions and their impacts on the sustainability of campuses, in addition to the need to better understand and study the connections between energy use and energy efficiency in university campuses. An integrated approach to different energy strategies, in parallel with the knowledge of available technologies and the commitment of university stakeholders, in partnership with government support and energy concessionaires, is essential to improve energy performance and reduce the energy footprint of the universities.

Keywords: Universities · Energy Efficiency · Energy Actions · Sustainable Campus

1 Introduction

Higher Education institutions (HEIs) should be at the forefront of research and development efforts on sustainable energy transition towards achieving the 2030 Sustainable Development Goals (SDGs). University campuses are like small-town ecosystems and thus constitute an important case study and a suitable field for urban experimentation [1]. Indeed, education is identified as the most effective means in the quest to achieve SDGs [2], and universities have a responsibility in promoting an energy transformation due to their leading role in training future leaders and decision-makers; ability to address environmental and socioeconomic problems; ability to induce collaboration between different stakeholders; and responsibility as social entities to meet emerging social needs [2, 3].

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The incorporation of approaches towards energy efficiency and renewable energy use at HEIs has been largely argued in literature. Universities use 3 to 5 more times energy than schools [4] and consume 60% more energy than commercial offices [5]. Universities use energy for various purposes and the pattern of energy use is defined by factors such as events and teaching schedules, occupancy, building size and type, and the equipment used. For that, there are differences concerning energy consumption on university campuses, mostly due to the influence of seasonal factors on heating (or cooling) the buildings.

Buildings account for a large amount of energy consumption and carbon emissions on university campuses. Worldwide, 30% of all primary energy is used in buildings, generating 8% of energy-related carbon dioxide emissions [6]. A building emits greenhouse gases (GHG) during different phases, but the largest portion of the GHG emissions is associated with the operational phase, about 75% of their entire lifecycle [7]. The World Green Building Council has issued a bold vision for buildings and infrastructure to reach 40% fewer carbon emissions by 2030 [7]. To achieve this goal, the HEI must take the responsibility to demonstrate an energy reduction commitment.

However, there is still no consolidation of strategies or difficulties faced in adopting energetic sustainable practices in universities. Senior university management does not have guidance on which energy management practices are most widespread and their effective results in reducing energy consumption in institutions. Sustainability international rankings, such as the Greenmetric ranking, also have no clear methodology to evaluate and compare university campuses concerning energy consumption and climate change criteria [8].

This study sought to identify the main sustainable energy management actions implemented in HEIs. Understanding the efforts that HEIs are adopting toward energy efficiency and renewable energy use can demonstrate research gaps and direct the action of universities, since this may lead to improvements not only concerning maximizing the use of their energy resources but also in terms of reducing the effects of climate change. In addition to the tangible and measurable impacts, these actions could allow the academic community to learn and explore innovative solutions and help society get involved in the incorporation of sustainability in all its dimensions.

2 Research Strategy

To answer what are the main sustainable energy management actions on university campuses, a bibliographic survey in the Web of Science database was carried out considering a set of search strings (Fig. 1) related to the terms universities, sustainability, and action, with a focus on energy management in HEIs. 46 articles were selected, categorized, and analyzed to obtain a holistic view of the main sustainable mechanisms for managing energy use in HEIs.

Fig. 1. Summary diagram of the research strategy adopted.

3 Results

The studies were categorized into two major groups: i) energy-saving actions and ii) energy-generation actions (Table 1). The energy-saving actions grouped actions related to energy efficiency practices in buildings management [9], consumption estimates at universities [8], the level of engagement in energy efficiency measures [1], critical analysis [10], and obstacles [11] in the energy actions of the campuses. Energy-generation actions grouped the actions related to the energy matrix of universities [12], the adoption of hybrid renewable energy systems [13], and alternative energy sources [14]. The main findings are described below.

3.1 Energy-Saving Actions

The main consumers of electricity in universities are lighting, ventilation, and cooling [1]. These systems are directly related to student activities and building type, factors that significantly contribute to the electricity consumption of a campus. Energy performance improvement and its monitoring are recognized as the first step for assessing and managing campus energy transitions [8].

Buildings that serve multiple functions consume more electricity as more types of appliances are used for different purposes [1]. The classification of buildings according to their energetic consumption is important to track, evaluate, and assist in readjustment and/or decision-making that best allocates resources to achieve low-impact infrastructure management in HEIs [4, 15]. Yoshida et al. [15] ranked energy consumption in buildings on a Japanese campus and guided actions that reduced 22% of campus energy use. In Category I, buildings with low energy density, the strategy was to adjust the energy system to people's daily routines; in Category II, buildings with high energy density, the strategy was energy conservation; in Category III, large-scale facilities such as hospital, the strategy was to outsource energy management.

Conducting energy audits is important to determine the university's energy profile, determine energy-saving options, and reflect the degree of compliance with energy efficiency standards [12, 16]. Shcherbak et al. [12] carried out a comparative analysis of

Table 1. Categorization of studies related to energy actions in universities.

Type	Papers		Focus	Papers	
	Number	%		Number	%
Energy-saving actions	28	61	Energy profiles	8	17.5
			Efficient electricity management	7	15.2
			Improving building envelope/Efficient HVAC systems	4	8.7
			Energy saving stimation	3	6.5
			Efficient appliances	2	4.3
			Efficient HVAC systems	2	4.3
			Environmental certification	1	2.2
			Passive design strategies	1	2.2
Energy-generation actions	18	39	Solar Photovoltaic (PV)	10	21.8
			Combined heat and power	4	8.7
			Biomass	2	4.3
			Renewable energy systems	2	4.3
	TOTAL			46	100.0

standards for certification of buildings by the level of energy efficiency on campus in Ukraine and found that all buildings in terms of energy consumption and energy efficiency belong to categories of low-level energy efficiency. Günkaya et al. [16] found that on a campus in Turkey, the building's annual heat requirement was considered higher than the heating requirement. To reduce heat losses, external insulation and double-glazing applications were considered as alternatives. However, these options would be greater resulting in environmental impacts. The energy audit should be used in combination with an ample approach such as Life Cycle Assessment.

The social factor must be considered to discover the behavioural responses of the occupants and their willingness to save energy [10]. For example, the energy demand during the academic calendar [17] and the vacation period are reduced and vary according to the different academic disciplines [1]. On Australian university campuses, there was a 5% reduction in campus energy consumption when changing from semester to trimester. This reduction occurred in teaching buildings while in buildings used for research, there was an increase in energy consumption. The results suggest that the standard of occupancy conditions should be adequately analyzed in the campus's energy management and carbon reduction policy [17].

By identifying a set of building energetic performances, decision-makers can estimate energy savings [17], control or manage building energy [18], adopt efficient appliances [19], adopt an energy-efficient measure [20], intervention planning [21], and change the user behaviour [22]. At the University of Zaragoza, Spain, an IoT ecosystem was implemented to monitor CO_2 and energy consumption in the classrooms and support research projects and institutional initiatives toward energy efficiency [23]. In Hong Kong, the average energy efficiency of educational buildings is 0.87, which means that 13% of the total energy consumption can be saved [18].

Fonseca et al. [21] designed a building renovation plan for a Portuguese university campus based on replacing the current lighting with LEDs and installing a photovoltaic system that achieved energy savings of 20%, with 27.5% of the consumed energy supplied by the photovoltaic system. The adoption of more efficient light bulbs; the replacement of ferromagnetic ballasts with electronic ones; and the installation of presence sensors in toilets would lead to a consumption reduction of about 26,123 kWh/year in the cost of electricity, avoiding the emission of 3,704 $kgCO_2$/year [24].

Efficient Heating, Ventilating, and Air Conditioning (HVAC) systems are mandatory to obtain high energy efficiency in buildings. In Brazilian public buildings is possible to reduce 30% to 50% of energy consumption by adopting low-cost technical and management measures [25]. When applying Data Envelopment Analysis (DEA) to evaluate and improve the energy efficiency of the internal spaces of buildings at a Brazilian University, considering lighting and air conditioning, it was observed that all classrooms were inefficient. The DEA model achieved a reduction of installed power of 43.5% and 22.7% (lighting and air conditioning systems) [25]. Liao & Liu [26] used the DEA model to investigate energy savings by recycling and reuse of rainwater in Taiwan, as a passive strategy. Recovering heat from wastewater discharged from showers was evaluated at a university sports facility in the United Kingdom [27]. Measurements of performance on different flow rates showed that over 50% of the heat in the wastewater could be recovered.

Improvement of the building envelope and efficient HVAC were important issues in renovation building plans [20, 28]. Proper retrofit actions can reduce buildings' energy demand for heating, cooling, and lighting by more than 60% at Balıkesir University (Turkey), with wall and roof insulation being the best passive retrofit actions in all buildings [20]. The main building envelope measures to improve the energy efficiency of the buildings were the application of an external thermal insulation layer on the walls of the classrooms, insulating the pipework and valves on heating systems, replacement of the existing windows by double glazing ones with thermal, correct use of shading in the classroom, airtightness, and replacement of fans and lamps [20, 24, 28]. In general, energy saving between 14 and 31% is possible with the addition of thermal insulation on external walls [20].

Sesana et al. [28] developed a Methodology for Energy Efficient Building Refurbishment to measure energy performance in historic buildings on Italy campus. The authors showed that energy use in existing buildings can be significantly reduced through a suitable retrofit. However, not all energy-retrofit actions are suitable and efficient. It is necessary to draw up a retrofit plan consisting of measures that provide relatively energy savings with low investment costs [20].

The investment required to implement energy efficiency measures can be three times less than capital inputs to increase the same amount of energy production [12]. Nunayon et al. [9] identified drivers of efficient electricity management, highlighting the vision and objective of an energy management program, knowledge and skills, risk identification, and effective communication between relevant stakeholders. In Madrid, the efficiency actions include the creation of the EcoCampus office, the introduction of environmental criteria in public tender procedures, the energy audits of buildings, the implementation of initiatives in lighting systems and information systems, the installation of thermostatic valves in radiators, and the increase of its renewable energy pool [29]. Lo [31] showed that China's HEIs have implemented non-technical and technical energy conservation measures. The non-technical initiatives were the institutionalization of energy conservation; energy conservation mechanisms; restriction of electricity use; extension of winter holidays; and awareness-raising measures. Technical initiatives are limited by a lack of funding and target LED and solar-powered lighting, compact fluorescent lighting, and infrared lighting controls. Murshed [31] reiterates that proper implementation of techniques for conserving electricity can reduce electricity bills by nearly a third and a 5% reduction in total on-campus electricity demand in Bangladesh.

Sustainable international rankings and environmental certificates do not guide or guarantee the energy efficiency of buildings [8, 32]. Chen et al. [32] compared the energy performance of Ohio State University buildings and showed that one of the LEED buildings consumed twice the predicted energy use while causing occupant dissatisfaction. Sonetti & Cottafava [8] compared the consumption profile of a Japanese and Italian university and although the universities have different features, functions, and occupancy patterns, in 2015 were situated in the same density area of values for the Energy and Climate Change category of Greenmetric ranking.

The adoption of energy-efficient buildings can be hampered by the lack of legal requirements, lack of qualified professionals, lack of customer demand, inadequate heat metering reform, underperformance of energy service companies, inadequate knowledge and information, investment by schools, lack of government funding, quality problems in energy conservation products, and low availability of green products in the market [11, 30].

3.2 Energy-Generation Actions

The implementation of photovoltaic (PV) solar energy systems is the main research topic of the studies (21.8% of the articles), the most implanted renewable energy system in the world [11] and in universities [1]. Most studies sought to evaluate the economic viability of this system in generating energy and reducing GHG emissions from universities [33, 34].

Mohammadalizadehkorde & Weaver [34] showed that 13 buildings at Texas State University (USA) could achieve annual electricity savings of 15.39 GWh - representing 17% of their annual energy costs by implementing energy efficiency projects. The investments in the projects will cost nearly $12 million, with the most expressive investment on solar panel installation and a payback return of 18 years. In addition, on energy savings, CO_2 emissions will be reduced by 12,561 metric tons annually, with a rate of savings of about 0.82 $kgCO_2/kWh$.

Karanam & Chang [33] analyzed the economic feasibility of solar PV systems on rooftops of the University of New Haven's Celentano. The study shows that the Net Present Value (NPV) is $121,134 and the payback period is 10.5 years. The energy generation for 2019 was 73,273 kWh and one panel among 226 panels generates approximately 324 kWh/year. Also recycling the PV panel at the end of its life could obtain an additional benefit of 4.3% of the total expected revenue.

Hasapis et al. [35] analyzed that the deployment of PV energy on a Greece campus could provide around 1,899 MWh of electricity annually, which represents around 47% of the campus's annual electricity consumption and reduce 1,234 tones of CO_2 that would be emitted by the diesel thermoelectric plant to generate the corresponding amount of energy. At a Spain university, the optimal PV power would maximize emissions savings, guarantee the best economic return, and coincide with the maximum solar potential of the Campus (around 3.3 MW). Approximately 77% of PV electricity production would be consumed locally, which would represent coverage of around 40% of electricity consumption and reduce between 619 and 1400 tCO_2e, equivalent to a 13–30% reduction over 2016 campus emissions [2].

The possibilities of integrating solar energy with fossil fuel-based energy were analyzed as a backup for periods of insufficient and unreliable supply from autonomous renewable energy system technologies [13, 36]. Ajiboye et al. [13] showed that the option of a hybrid renewable energy system based on a PV-Diesel-Grid-battery energy storage system is the best configuration to meet Covenant University's load demands in terms of reducing the cost of electricity. At Silliman University, Philippines, the components of an ideal solar-diesel grid system, with a renewable energy fraction of 15%, the most profitable system consists of 500 kW photovoltaic solar energy, three diesel generators, and a connection to the grid. This has an initial capital cost of $1,222,222; the Cost of energy is also $0.227/kWh, and the NPC is $11,237,959 [36].

Perea-Moreno et al. [14] analyzed the use of loquat seed as biofuel for the heated swimming pool at a university in Spain, achieving a reduction of 147, 973.8 kg of CO_2 in emissions and savings of 72.78% compared to the previous fuel oil installation. Tian et al. [37] developed an energy system carbon-neutral optimization model considering earth source heat, lake source cooling, on-site renewable electricity generation, and sustainable peak heating systems to minimize the annual total cost of the main campus of Cornell University (USA). Based on the current electrical energy mix, GHG emissions are substantially reduced to 8% to 17% of the 2020 value.

Most studies that report failures in the adoption of renewable energy sources in universities are related to the implementation of PV systems [10]. The biggest obstacles identified were the lack of support and involvement from the university administration [11] and the lack of financial resources [5]. Geh et al. [11] showed five barriers critical related to cost and funding: lack of financial resources, high upfront cost, long payback period, and scarcity of power purchase agreement or lease acquisition options. Regarding institution-related barriers, there was a lack of green building targets, a lack of policy direction, and a lack of reporting sustainability performance. The government-related barriers were the lack of incentives, lack of demand from project financiers, and inadequate infrastructure funding.

4 Discussion

Energy efficiency measures in buildings were the focus of the studies and should be a priority strategy in campus decarbonization. Measures to improve building envelopes, HVAC systems, and the adoption of efficient appliances aim to save energy in universities. However, they are intrinsically linked to the thermal comfort of users and will probably become more frequent with climate change. In this way, the balance between energy efficiency, thermal comfort, and budget management should guide new discussion scenarios at universities and promote the creation of sustainable solutions and environmental education.

However, there has been no research on strategies for raising user awareness and promoting engagement in energy-saving long-term measures in university buildings. User behaviour directly affects energy consumption and drives the implementation of sustainable measures in universities. HEIs should closely monitor the user's behaviours and the performance of their buildings and refine their policies, and procedures to address energetic problems. The best way to improve the performance of existing buildings towards zero energy is an integrated approach of different energy strategies, working in parallel, that addresses behaviour, equipment efficiency, on-site renewable energy generation, and storage power [21].

Renewable energy provides around 15.5% of the energy used in the world's buildings [7]. In universities, they represent minimal shares in energy generation and are little explored [1]. Among renewable alternatives, solar energy predominates but is still in the design and economic viability prospecting phase. Biomass, wind, and geothermal are alternatives seen as secondary sources and, although renewable energy can represent 100% of energy generation, no study presents this as a hypothesis.

Energy efficiency is more common than investing in renewable energy, probably because it encompasses a larger investment and technological changes. Regarding challenges to the implementation of renewable energy, lack of funding was the most predominant. Globally, only a few overarching targets exist for the use of renewables in buildings, and/or for renewables to supply a rising share of heating and cooling needs [7]. Universities must create committees for existing administrative procedures in implementing funds for energy efficiency management. The full support of top management is essential for the continuous improvement of energy efficiency programs. The need for government support is essential to increase the picture of these energies in universities. Goals need to be defined, especially considering that universities are public institutions and need to lead society in global climate objectives.

5 Conclusions

Universities are complex, polycentric, and multistakeholder organizations, for which energy management can represent an opportunity to promote new institutional governance mechanisms. However, the reviewed literature shows that energetic management actions are emergent and focused on some energetic efficiency buildings measures. The energy-efficiency agenda is not part of the top management's policies and there is a lack of leadership that coherently guides the internal decision-making processes, the allocation of resources, and the system of incentives for teaching and research under the aspects of sustainable development. Funding is a big barrier. However, there will only be resources when senior management is aware of the importance of sustainability practices in the growth of university campuses.

HEIs will need to transition from the current partial and piecemeal tactic, taking a proactive approach, reviewing their current operating models, and increasing their levels of ambition to bring about the change needed for society to achieve carbon-neutral goals. These institutional changes will need political support at the government level, as HEIs are intrinsically linked and influenced by external factors. Only through a joint and coordinated approach will HEIs be able to successfully expand the lessons learned to society through the dissemination of their energetic results and the management of university campuses.

More empirical literature is needed, as the disproportion between the information on the description of actions and their impacts is notorious. There is also a need to better understand and study the connections between energy use and energy efficiency in universities, as this can maximize the use of their energy resources and reduce the carbon footprint.

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Hybrid Renewable Energy to Greener and Smarter Cities: A Case Study of Kayseri Province

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Abstract. In this study, a hybrid energy system was implemented to fulfill the electricity requirements of the trams operating in Kayseri province. The tram's annual electricity consumption data was acquired on a monthly basis from the local electricity company in Kayseri. Utilizing the obtained data, energy and cost simulations were conducted employing the Homer-Pro program. The primary objective of this investigation is to enhance sustainability while satisfying electricity demands with minimal carbon emissions. Consequently, the established hybrid energy system incorporates renewable energy sources, specifically wind, solar, and biomass energy, with the inclusion of batteries for energy storage. Furthermore, generators and converters are integrated for energy conversion purposes. The study encompasses a detailed cost analysis to identify the most economically efficient hybrid energy system, determined through optimization studies. Through this research, it is anticipated that the implementation of such a system will significantly diminish carbon emissions in Kayseri, contributing to a substantial increase in sustainability.

Keywords: Homer Pro · Smart City · Sustainability · Hybrid Energy · Kayseri

1 Introduction

The foundation of societal prosperity and the impetus behind its advancement is energy. Future sources of energy must be both cost-effective and sustainable while maintaining environmental friendliness. Over time, renewable energy sources are anticipated to supplant conventional fossil fuels [1]. The persistent reliance on fossil fuel-based energy sources, such as coal, oil, and gas, to meet the escalating global energy demands and population growth has given rise to various issues. These include the depletion of fossil fuel reserves, the emission of greenhouse gases, and other environmental challenges [2]. Escalating concerns related to climate change and sustainability are exerting pressure to embrace more renewable resources and technologies [3]. Renewable energy sources possess the advantages of being limitless, environmentally friendly, and amenable to decentralized utilization. An additional benefit lies in their complementary nature and

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seamless integration, allowing for efficient collaboration. For instance, on days characterized by sunshine, cool temperatures, wind, and intermittent cloud cover, solar photovoltaic energy can generate electricity. On such occasions, strategically positioned wind turbines contribute additional electricity for both stand-alone and grid-connected applications [4]. Configurations of hybrid renewable energy systems are imperative for ensuring a secure and sustainable electricity supply. The intermittent nature of renewable resources can be addressed through the incorporation of hybrid sources and efficient storage solutions [5]. The deployment of hybrid solar-wind renewable energy systems is experiencing daily growth and has witnessed substantial expansion in the past few decades, contributing significantly to global electricity production [6]. The burgeoning popularity of Hybrid Renewable Energy Systems (HRES) for meeting specific energy demands is evident in the existing literature on HRES modelling. HRESs find extensive application in remote region power setups and are increasingly becoming economically viable in scenarios where expanding the grid supply would be cost-prohibitive [7]. The optimization of hybrid renewable energy systems involves the meticulous selection of components, determining their sizes, and formulating an effective operational strategy. This optimization aims to produce alternative energy solutions that are not only inexpensive but also reliable, efficient, and cost-effective.

Despite being endowed with abundant energy resources, Turkey relies on energy imports due to the limited availability of these resources. Currently, imports constitute more than half of the nation's primary energy consumption, and this percentage continues to escalate annually. Therefore, it becomes imperative for the country to realize renewable energy sources within a reasonable timeframe to meet its energy demands using domestic resources, including natural gas, oil, lignite, and hard coal [8]. Kayseri, ranking as the fifteenth most populous city in Turkey, experiences an increase in energy consumption commensurate with its urban size. In the conducted study, hybrid renewable energy systems were conceptualized and subjected to techno-economic analysis to fulfill the electrical energy requirements of trams in the city of Kayseri through entirely renewable methods. The tram system holds a pivotal role in public transportation for Kayseri, exhibiting substantial energy consumption, approximately 65,000 kWh/day. The project's objective is to establish a hybrid and renewable energy system to cater to the energy needs of public transportation. The environmental impact of the proposed project is minimal, and optimal costs have been assessed using the Homer Pro program.

2 Methodology

2.1 HOMER Simulation and Optimization

The hybrid renewable energy system in this research is developed using the HOMER-Pro Programming, a software tool developed by the National Renewable Energy Laboratory in the United States. This tool facilitates simulation and design under ideal circumstances with predetermined limitations. A novel programming technique known as HOMER is employed to generate sophisticated models for grid-integrated and hybrid energy system planning [9]. HOMER Pro incorporates a range of energy plant components, including wind turbines (WT), photovoltaic arrays (PV), fuel cells, small hydropower, biomass, converters, batteries, and traditional generators [10].

The Homer program requires various datasets, encompassing information related to the types of renewable energy sources, electric load data, and cost data. Homer serves not only as an energy analysis tool but also as software capable of conducting cost analysis [11]. Initially, understanding the electricity load to be addressed was imperative. To obtain this information, communication was established with the city's electricity company, and the daily and monthly electricity consumption by all trams was meticulously calculated. The determined electric consumption data were then input into Homer, enabling the generation of an electric charge profile. The average daily electrical load was computed to be 64,341 kWh (Fig. 1).

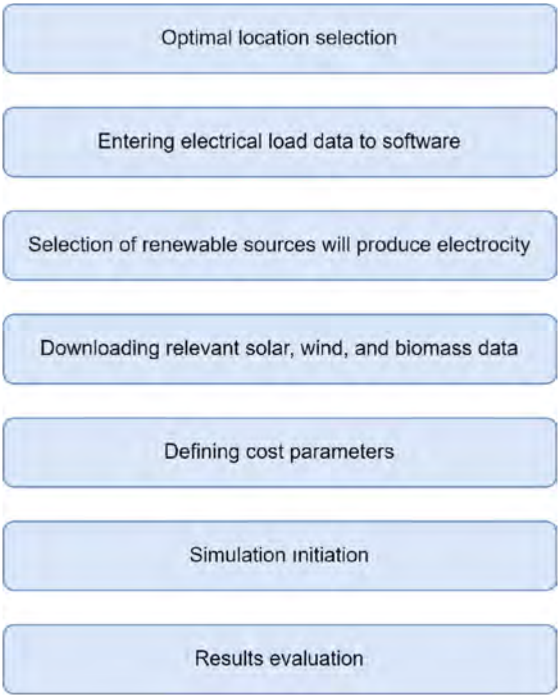

Fig. 1. Methodology flowchart.

In this study, three distinct types of renewable energy resources were employed as follows: biomass, wind, and solar. This selection was driven by the favourable conditions for these energy systems in the geographical location of Kayseri province. The specific location chosen for implementation is illustrated in Fig. 2.

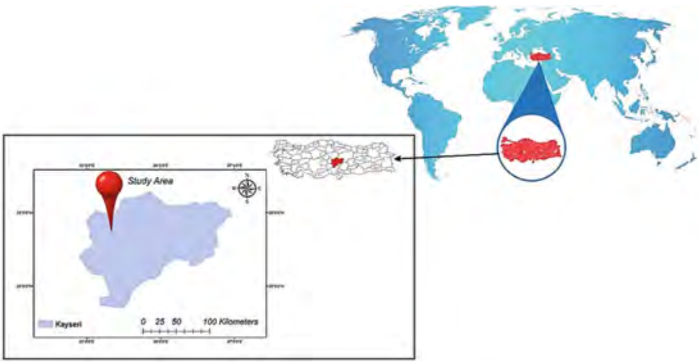

Fig. 2. Geographical location of the study area.

Simulations were conducted to assess the costs and energy returns associated with different combinations of biomass, wind, and solar energy resources. Through comparisons, the option with the lowest cost was identified. The study presents costs in terms of net present cost (NPC). The system was conceptualized as a 25-year project, encompassing replacement costs and operating expenses incurred over this duration in the calculations. Following the determination of the electrical load, the next critical step involved obtaining the necessary data for the selected renewable energy systems. For the Photovoltaic Module (PV), clarity and daily radiation values specific to the chosen location were essential. These data were sourced from the internet using the Homer Pro software.

The maximum clearness and radiation occur in July, with values of 7.35 kWh/m^2 for radiation and a clearness index of 0.651. The subsequent step involves defining wind energy data, wherein the selection of the optimal wind turbine (WT) becomes crucial. Initial considerations involve importing and evaluating wind speed values at the chosen location based on meteorological data. The maximum average wind speed, observed in February, is 5.46 m/s, while the yearly average for the selected location stands at 4.79 m/s. The subsequent phase involves the integration of the biomass renewable energy system into the hybrid system. The critical aspect here is the availability of data. The daily average biomass mass required for the biomass system, measured in tons, was obtained from the literature. Based on the annual data, the average daily biomass mass was determined to be 25,640 tons [12].

Generic 100 kWh Li-on batteries were used for storage in the study. In addition, a biogas generator and converter were used to provide energy conversion. Cost calculations in the project are calculated according to the default cost values of the program. System Structure in the established system, the hybrid operation of 3 different renewable energy systems was examined. In the study, the operating and cost efficiency of different energy system combinations were also examined. Figure 3 shows the structure of the optimally selected hybrid system.

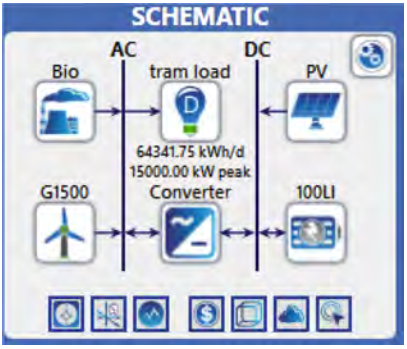

Fig. 3. Schematic of designed structure.

To enhance the visual comprehensibility of the conducted work, a symbolic design was created using the SolidWorks 3D design program. The 3D design of the renewable energy system is depicted in Fig. 4.

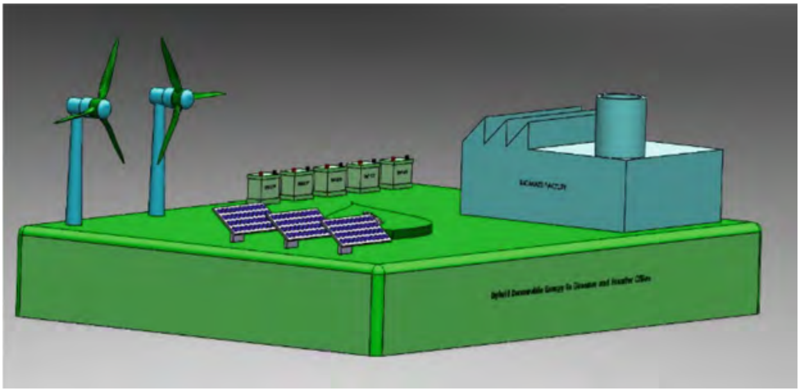

Fig. 4. Visual representation of hybrid energy system.

3 Results

The outcome of the simulations revealed that the minimum cost required to fulfil the necessary electricity demand amounted to 179 million dollars (M$). The categorized costs are presented in Fig. 5. The following are the costs resulting from various hybrid systems and simulations.

Architecture							
PV (kW)	G1500	Bio (kW)	100LI (#)	Converter (kW)	Dispatch	NPC ($)	LCOE ($/kWh)
13,834	10	3,000	819	9,540	LF	$179M	$0.591
13,155	14		1,095	12,155	CC	$210M	$0.693
	25	3,000	1,587	11,613	CC	$283M	$0.933
	25		2,581	20,081	CC	$379M	$1.25
64,342		3,000	1,825	15,001	LF	$382M	$1.26
63,385			2,650	29,561	CC	$462M	$1.53

Fig. 5. Cost analyses results of different structures.

In light of the optimization results, it was observed that opting not to install a hybrid system but relying solely on a renewable energy system had a significantly adverse impact on costs. Additionally, it was noted that forgoing the establishment of a biomass facility resulted in a cost impact of $41 million.

In the research, Fig. 6 illustrates the contribution of each renewable energy source to the overall energy production. This figure delineates the electric production values of three distinct renewable energy systems, namely biomass, wind turbines, and solar panels. Given that the maximum radiation and clearness values occur in July, it is evident that higher electric production is observed during that month.

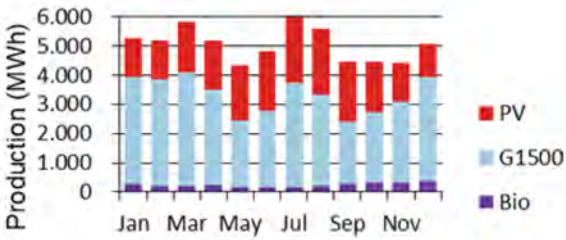

Fig. 6. Electrical production values of 3 different renewable energy systems.

3.1 Cost Analysis

The cost analysis in the study utilized the Homer-Pro program to determine the minimum monetary outlay for the desired energy output. This research encompassed a 25-year period, including installation costs, maintenance costs, and operating costs. The optimization results are detailed in Table 1. The cost analysis revealed that, over the 25-year duration of the project, the installation cost of renewable energy surpassed the operating cost. Furthermore, Fig. 7 provides a classification of the costs associated with different renewable energies in hybrid systems. According to the obtained data, it was observed that battery installation incurred relatively higher costs compared to other systems.

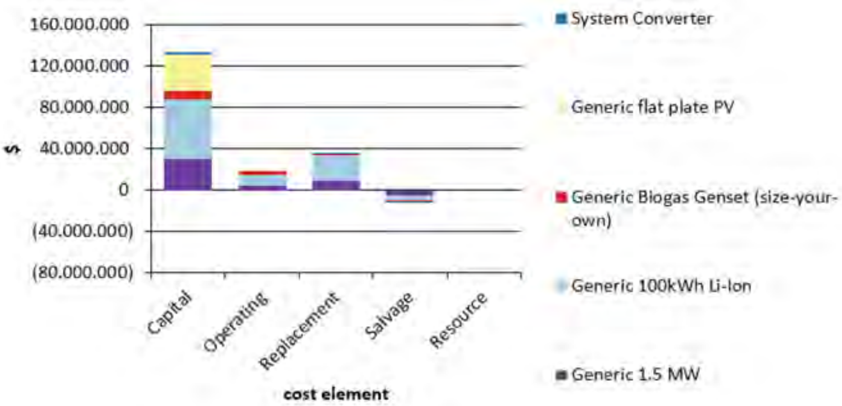

Fig. 7. Cost values of optimized hybrid design.

Table 1. Cost values during the project time.

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1.5 MW	\$30.0M	\$3.88M	\$9.56M	−\$5.39M	\$0.00M	\$38.1M
Generic 100 kWh Li-Ion	\$57.3M	\$10.6M	\$24.3M	−\$4.58M	\$0.00M	\$87.7M
Generic Biogas Genset	\$9.00M	\$3.64M	\$1.11M	−\$743,378M	\$0.00M	\$13.0M
Generic flat plate PV	\$34.6M	\$1.79M	\$0.00M	\$0.00M	\$0.00M	\$34.6M
System Converter	\$2.86M	\$0.00M	\$1.21M	−\$228,537M	\$0.00M	\$3.85M
System	\$134M	\$19.9M	\$36.2M	−\$10.9M	\$0.00M	\$179M

3.2 Engineering Analysis

The Generic PV system boasts a nominal capacity of 13,834 kW, with an annual production reaching 20,720,428 kWh/yr. Figure 8 illustrates the electrical production of the PV system by the day of the year, with the y-axis representing hours of the day. As depicted in this illustration, the production during midday is notably higher compared to the morning and night hours.

The power output from the Generic wind turbine system, with a rating of 15,000 kW, reaches 37,096,044 kWh/yr. Figure 9 visually represents the electrical production of the wind turbine by the day of the year, with the y-axis denoting hours of the day. As indicated in this illustration, the production on different days of the year is not constant, reflecting the proportional influence of wind resource data. Production tends to increase with higher

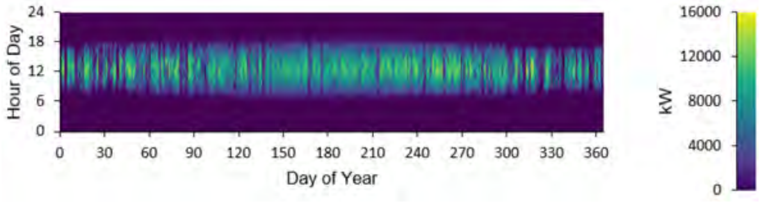

Fig. 8. Daily electrical production of PV.

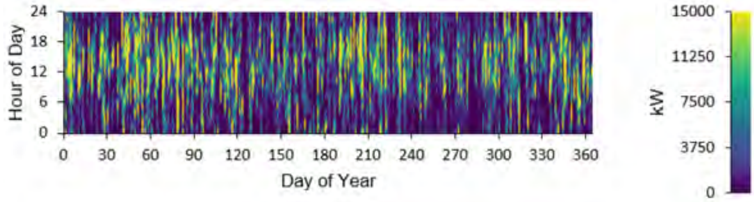

Fig. 9. Electrical production of wind turbines.

wind speeds. Additionally, the power output from the Generic generator system, with a 3,000-kW rating and utilizing Biogas as fuel, amounts to 2,805,703 kWh/yr.

3.3 Electrical Summary

The total amount of electricity obtained is calculated as 60,622,174 kWh/year. This quantity of electricity significantly exceeds the electrical load required for the tram system. If the surplus electricity is connected to the grid, it has the potential to meet the electricity needs of thousands of households.

4 Conclusions

The outcomes of our research underscore the positive impacts of widespread adoption of hybrid energy systems in large cities. While the use of renewable energy is progressively aligning with sustainable development goals (SDGs) in Turkey, the research aims to further enhance this integration through hybrid systems. The combination of diverse energy sources has notably reduced costs. To mitigate climate change, the global implementation of such systems must be intensified. The overarching objectives of the research are summarized as follows:

- Reducing carbon emission;
- Increasing awareness related to sustainability;
- Representing advantages of hybrid energy;
- Providing renewable energy for public transportation;
- Optimizing energy plants with minimum cost and maximum efficiency.

It is imperative to prioritize the United Nations' sustainable development goals and undertake projects aligned with these objectives. One of the key findings of the conducted research is that hybrid systems entail high installation costs, which could be mitigated through advancements in technology and production methods. The study suggests that future research endeavours should concentrate on reducing the production cost of renewable energy systems. The optimization results presented in this research underscore the significance of prolonging the lifespan of materials used in the market, as this would contribute to the widespread adoption of hybrid systems. According to the optimization results, the cost of meeting the energy consumption of trams in Kayseri entirely with renewable energy sources was determined to be 179M$. The established plant incorporates wind energy, solar energy, biomass energy, and batteries, with 95% of the required energy obtained from solar and wind sources. The total energy yield was found to be 60,622,174 kWh per year, significantly surpassing the tram's energy requirements. Consequently, the surplus energy can be fed into the grid, potentially yielding profits. The lithium-ion battery cost constitutes 50% of the overall project cost. The project, designed to fulfil a 25-year need, entails an installation cost of 133M$, with the remaining costs attributed to replacement and operation. The reduction of these costs can be achieved through advancements in technology and ongoing research.

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Innovation in Materials, Products and Systems

Disassembly and Structural Reuse Potential of Steel-Timber Shear Connections with Screws

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Abstract. The paper evaluates the disassembly capability and reuse potential of steel-timber shear connections. Experiments involving double shear configurations with coach screws of three diameters are detailed. Monotonic tests were first performed for each configuration to evaluate the stiffness, strength, and ductility. Counterparts were then tested under ten loading-unloading cycles, to 40% of the capacity obtained from the monotonic tests, to evaluate stiffness degradation characteristics, screw deformations, and cross-laminated timber (CLT) panel damage. After disassembly and measurements, the specimens were reassembled and tested up to failure. The measurements indicated that the secant stiffness enhances after the first loading cycle and is then largely constant to the tenth cycle. After disassembly, the screws had permanent deformations, and the timber panels indicated limited damage during the cyclic loading. The reassembled specimens had similar stiffness, strength, ductility, and failure modes as the monotonic test specimens. Based on test measurements, both the steel profile and the CLT panels have full structural reusability. The test results can be used as a measure for quantification of the structural reuse potential through an index that can be incorporated into established building circularity indicators.

Keywords: Steel-timber · Disassembly capability · Reuse potential · Circularity

1 Introduction

To achieve established reduction targets by 2030 and net-zero by 2050, innovative building systems such as steel-timber hybrids (STH) are needed. Building structures incorporating timber have the potential to contribute to reducing embodied carbon by 60%, storing sequestered carbon by up to 400% as well as can be designed for disassembly, compared with conventional concrete structures [1]. Steel-timber and timber-concrete solutions for multi-storey buildings highlighted the synergetic behaviour of the two

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materials [2]. Whilst timber-concrete hybrids were the subject of many studies, STH systems, particularly for taller structures, were less investigated.

Recently built six-storey educational and ten-storey residential STH buildings highlighted the benefits of such systems for reduced construction time (offsite manufacturing, design for assembly) and enhanced environmental sustainability (less embodied carbon and potential for disassembly and reuse at the end of life) compared to other composite or conventional building systems [3]. Steel-timber hybrid structures are considered lightweight systems suitable for prefabricated modular buildings [4] and consist mainly of steel columns with steel or timber beams with CLT or LVL slabs [5, 6]. To achieve composite action, steel-timber floor shear connections can be either dry, by using mechanical fasteners, or wet, requiring the use of epoxy-based resins. The latter offers enhanced initial bending stiffness, yet the ultimate behaviour is associated with brittle failures compared to dry connections [7]. The use of wet connections may impair the disassembly at the end of life, rendering them less circular.

Circularity is a systemic approach that aims to eliminate waste and optimise resource utilisation. This is typically measured through indicators that provide information about the extent to which resources are used efficiently, recycled, and kept within a closed loop. Within the main principles of circularity in buildings, slowing the resource loops refers to decelerating the resource flows by improving their utilisation and expanding their valuable lifespan. This refers to design for durability, long life and life extension, for adaptability and reversibility, reuse and repurpose. Dry shear connections in STH floors align with these principles of circularity, enabling disassembly and reuse and repurpose of the components with minimal or no loss of mechanical properties.

Experimental and numerical studies on conventional shear connections for STH floors exist, focussing primarily on structural performance. These include screwed, bolted, or grouted connections that were tested either under monotonic or cyclic loading to failure. In line with circularity drivers, evaluation of the constructability and disassembly and reuse potential is essential but has not been evaluated. This paper evaluates the disassembly capability of screwed steel-timber shear connections, tested under in-service cyclic loading, as well as the reassembly and structural reuse potential through testing. The experiments involved double-shear configurations with coach screws. After describing the testing methods and the main results, a qualitative discussion of the disassembly and reuse is undertaken.

2 Response of Steel-Timber Shear Connections

In steel timber shear connections, failure can typically occur by four governing modes. As illustrated in Fig. 1, the mechanisms developing in the shear connections are through: (1) screw shear failure when the shear resistance of the connector is relatively weak in comparison with the timber element, (2) timber crushing with elastic behaviour of the connector, with this response occurring when the connector is strong in relation to the wood materials; and mixed-mode failures such as (3) with connector plastic hinging and timber crushing, and (4) double hinging in the connector with timber crushing.

Tests on three types of self-tapping screws in STH shear connections exhibited ductile failure mode with post-elastic bending deformation and CLT panel crushing

[8]. Connections loaded perpendicular to the grain had higher strength, while those loaded parallel had greater stiffness. Longer fasteners increased connection strength. Closer spacing of fasteners decreased stiffness and connection strength. Push-off tests showed increased shear capacities with inclined screws but decreased stiffness, compared to perpendicularly installed screws [9]. The use of tapper washers increased stiffness but also caused shear damage. Screws with long shanks were recommended for good ductility, and multiple rows of screws resulted in decreased strength per connector.

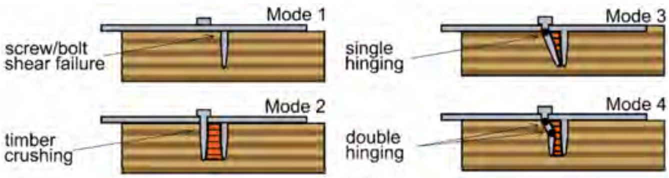

Fig. 1. Failure modes in steel-timber shear connections with screws.

Dry connections made using coach screws in steel-CLT shear connections demonstrated rather ductile behaviour [6]. Comparative wet connections had higher strengths and stiffnesses, but an overall more brittle response due to panel separation or glue fracture. Parallel to the grain, the load-slip responses were close to elastic-perfectly plastic, while in the perpendicular direction, there was hardening due to timber densification. The strength was higher perpendicular to the grain, but service stiffness was lower due to the lower elastic modulus of timber in that direction. Quasi-static cyclic tests were performed on steel-timber specimens with various types of shear connections, such as vertical or inclined self-tapping screws, epoxy resins, and glued steel slotted plates, among others [4]. As expected, dry connections with screws had lower strength and stiffness compared to systems with slotted plates and epoxies.

3 Experimental Assessment

3.1 Materials

The engineered timber employed in this study was a Cross-Laminated Timber (CLT) composed of three layers with a nominal thickness of 95 mm and a strength category of C24 spruce lamellae (softwood). Each layer was orthogonal to the subsequent at a 90-degree angle. Each layer measured approximately 32 mm in thickness, and the layer alignment was as follows: 32L/32 T/32L, where L indicates the longitudinal orientation and T the transverse orientation. The outer layers were aligned so that the load is applied in the direction parallel to the grain. For the push-out tests the CLT panels were 300 mm × 400 mm × 95 mm (width × height × thickness). Compression assessments were performed parallel to the grain on five CLT samples with an average size of 150 mm × 300 mm × 95 mm (width × height × thickness).

The specimens, shown in Fig. 2, were made up of two CLT panels that are linked to the flanges on both sides of an S235 hot-rolled open section with a characteristic yield strength of 235 MPa. The dimensions of the profile were: section depth h = 161.8 mm, section depth b = 154.4 mm, flange thickness of t_f = 11.5 mm, and web thickness of t_w = 8.0 mm. To connect the CLT panels to the steel beam, coach screws with hexagon head, made of hardened steel and complementary washers were used. The screws were of 8 mm, 10 mm and 12 mm diameters, each respective diameter with 80 mm length, grade 4.8, 340 MPa nominal yield strength and 420 MPa nominal ultimate strength.

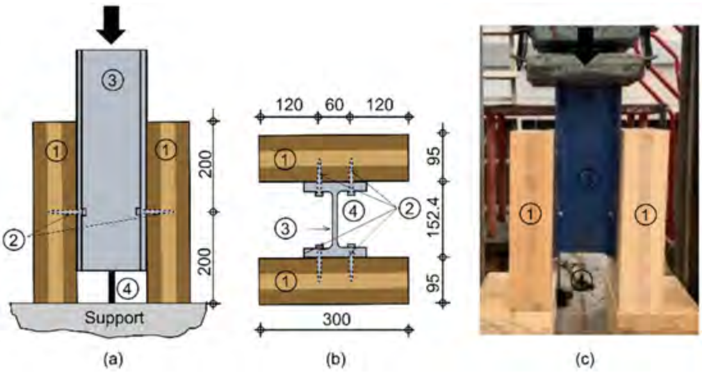

Fig. 2. Details of the test specimens: a) schematic front view, b) top view, c) view of a test specimen (legend: (1) CLT panel, (2) screws, (3) steel profile, (4) transducer, arrow indicates reaction point).

3.2 Specimens

A total of twelve specimens were prepared for testing. These included six for the monotonic test (M) and six for the reuse potential test (R). The former tests involved testing to failure, whilst the later involved repeated cyclic loading, specimen disassembly and measurements, reassembly with new screws and testing to failure. For each test, two samples were used for each coach screw diameter to enable a comparison of the results. The specimens were identified based on their respective screw diameters, resulting in the specimen labels following the format X-Y-z, in which X is the loading protocol (X = M, R for monotonic and reuse potential, respectively), Y is the screw diameter (Y = 8, 10, or 12 mm), and z is for the specimen sequence (z = a,b). For example, specimen name R-12-b represents the case of the second specimen tested under the suggested reuse potential protocol, which used 12 mm screws.

The CLT was available in the form of full-sized boards with varying dimensions, which were cut in the workshop into 24 panels to the above-mentioned sizes. The supporting edge of each panel was smoothened with a planer to prevent any instability and to encourage uniform contact with the testing platform and eliminate any unequal load distribution throughout testing. For consistency, a 60 mm distance between the axis of the two screws was considered for all specimens. Transversely, 120 mm and longitudinally, 200 mm, were considered between the edge of the panel and the screws.

Prior to assembly, holes of half the size of the corresponding net screw diameters were predrilled in the timber panel to facilitate screw installation. The panels were attached to the steel column flanges using two coach screw connectors, washers, and a torque tool, as shown in Fig. 2. The torque tool was used to ensure the same level of tightness for all samples. Washers were used to enhance the contact area of the connectors with the panels, to ensure a smoother stress distribution at the connection. As seen in Fig. 2 the connectors were completely integrated in the panels, leaving no exposed smooth shank or inclination. The panels were orientated for the load to act out parallel to the grain direction of the outer panel.

3.3 Testing Procedures

As mentioned above, twelve tests were carried out, equally divided into monotonic tests to failure (M) and reuse potential tests (R), as shown in Fig. 3. The tests were carried out to understand the overall response, the disassembly capability and structural reuse potential. For this, a 1MN Avery Instron testing machine with a ball seating was used. The latter had the purpose to prevent development of any out-of-plane deformation that would induce bending moment in the connection. In the monotonic tests (M), and the post-reassembly phase of the reuse potential tests (R) a displacement rate of 1 mm/min was applied before deviation of linearity in the load-slip (F-δ) curve. This rate was then increased to 5 mm/min to failure. The F-δ curves and main structural parameters were recorded during the tests by the machine and additional transducers.

For the reuse potential tests (R), the average maximum strength of the corresponding monotonic tests (M) was used. The specimens were subjected to cycles starting from zero to 40% of the result obtained from the monotonic test. This complete cycle of loading and unloading was conducted ten times consecutively. After completion of the ten cycles, the specimen was removed from the testing rig and disassembled. The specimen was secured to prevent any movement during the disassembly process using clamps or vice grips. The screws were then loosened with a wrench due to limited accessibility. For deeper steel sections, electrical screwdrivers or similar tools can be used. Once the screws were sufficiently loosened, these were removed carefully to prevent any potential damage to the CLT panel or the steel sections. The damage length occurred in the timber panel was then measured with a ruler. Finally, the steel and timber elements were inspected separately for any visible damage.

New screws were installed into the pre-existing holes of the same specimen to evaluate the residual properties of the connection post-disassembly. After reassembly, as noted, the same procedure as for monotonic tests was applied. The load and slip were recorded by the machine and the additional transducer by a data logger. These data permit the evaluation of the main residual mechanical properties such as stiffness, strength, and ductility of the connection. In direct correlation with the monotonic tests, these give an indication of the structural reuse potential of the investigated connections.

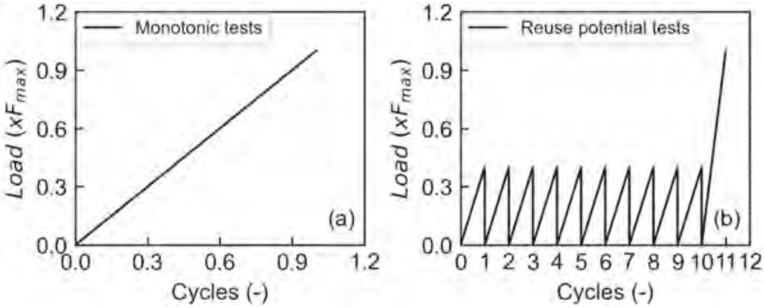

Fig. 3. Loading procedures: a) monotonic tests, b) reuse potential tests.

4 Test Results

Tables 1 and 2 and Figs. 4, 5, 6, 7 and 8 depict the main test results from the monotonic and the reuse potential tests. These include load-slip (F-δ) curves, failure kinematics, and the main response parameters. These are the secant stiffness at 40% ($k_{0.4}$) and 60% ($k_{0.6}$) of maximum capacity (F_{max}), the yield load (F_y), slip at yield (δ_y), ultimate slip (δ_u) corresponding to either slip at failure or 20% decrease from $F_{max,}$ and a slip ductility ratio ($\mu_\delta = \delta_u/\delta_y$). Additionally, for the reuse potential tests, $k_{I,0.4}$, $k_{I,0.4'}$, corresponding to the secant stiffness at 40% F_{max} for the first cycle, the tenth cycle prior to disassembly, respectively, parameters $k_{II,0.4}$ and $k_{II,0.6}$ for the reassembled case are also reported.

4.1 Monotonic Tests

Figure 4 show the F-δ curves for the tested specimens. The M-8 specimens experienced failure without demonstrating any hardening. The secant stiffness $k_{0.4}$ and $k_{0.6}$ varied between 2.85–3.00 kN/mm. Specimen M-8-1 exhibited a yield strength F_y of 19.1 kN, and a corresponding slip δ_y of 6.5 mm, while its peak strength F_{max} reached 26.6 kN with an ultimate slip δ_u of 13.8 mm. Specimen M-8-2 exhibited an F_y of 21.4 kN and a δ_y of 8.8 mm, an F_{max} of 28.2 kN with a δ_u of 15.1 mm.

The results obtained from the experiment indicated that the average yield and ultimate capacities were 20.3 kN and 27.4 kN, respectively. Additionally, the average yield and ultimate slips were found to be 6.46 mm and 15.4 mm, respectively. The screws experienced a brittle mode of failure in both specimens, with the connectors breaking at the interface between the smooth and the threaded shank. The occurrence of panel crushing or splitting was minimal. The observed failure mode indicates that the response was governed by the strength of the connectors, rather than the timber.

The M-10 specimens demonstrated ductility, evidenced by the plastic hinges in the screws. Their secant stiffness $k_{0.4}$ and $k_{0.6}$ varied between 3.41–6.08 kN/mm. For specimen M-10-1, F_y was 33.2 kN, δ_y was 5.9 mm. Its F_{max} was 40.5 kN, and δ_u 24.8 mm. Its counterpart, Specimen M-10-2 had a F_y of 26.0 kN, a δ_y 7.5 mm and reached an F_{max} of 31.7 kN with a δ_u of 21.5 mm. On average, the specimens exhibited average F_y and F_{max} of 29.6 kN and 36.1 kN, respectively.

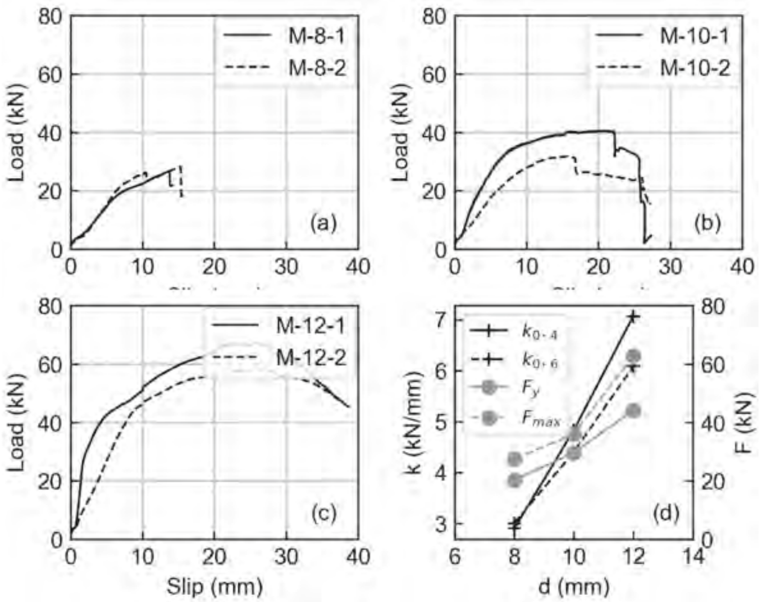

Fig. 4. Load-slip curves from monotonic tests for Specimens: a) M-8, b) M-10, c) M-12; d) the relationship between the screw diameter and stiffness and strengths.

The average δ_y and δ_u were 6.7 and 23.2 mm, respectively. From the load-slip curves, it was evident that the connections exhibited an elastic-plastic behaviour, undergoing plastic deformation up to the point of failure. All screws had a plastic hinge indicating ductile forms of failure. For M-10-1 there was a notable timber compression where the split measured 17 mm from the initial screw axis to its ultimate position prior to failure.

The M-12 connections also exhibited a ductile response. Their secant stiffness varied between 5.28–8.87 kN/mm. For Specimen M-12-1, the F_y was 42.0 kN with an associated δ_y of 4.1 mm, while its F_{max} reached 67.2 kN at a δ_u of 34.4 mm. Meanwhile, Specimen M-12-2 presented an F_y of 42.0 kN at a δ_u of 4.1 mm, an F_{max} of 58.3 kN at a δ_u of 38.0 mm. The average F_y and F_{max} were 44.2 kN and 62.7 kN, respectively, whilst the average δ_y and δ_u were 6.5 mm and 36.2 mm, respectively.

As indicated by the F-δ relationships, the specimens predominantly exhibited an elastic-plastic behaviour. This is consistent with the test observations indicating the development of plastic hinge in the screws that remained embedded in the panel upon failure, which was more visible than that shown in the other tests. Comparatively to M-8 and M-10, more evident timber crushing occurred for these specimens. From Fig. 4d and Table 1 it is also shown that stiffness ($k_{0.4}$ and $k_{0.6}$), strengths (F_y and F_{max}), and slip ductility ratio (μ_δ) increase with screw diameter. Note that the bolded numbers in Table 1 and 2 represent the average values from two tests, followed by the standard deviation.

Table 1. Results from the monotonic tests.

Specimen	$k_{0.4}$ (kN/mm)	$k_{0.6}$ (kN/mm)	F_y (kN)	F_{max} (kN)	δ_y (mm)	δ_u (mm)	μ_δ (-)
M-8-1	2.85	2.92	19.10	26.62	6.50	13.77	2.12
M-8-2	2.94	3.08	21.40	28.20	6.80	15.10	2.22
M-8	**2.89 ± 0.06**	**3.00 ± 0.11**	**20.25 ± 1.63**	**27.41 ± 1.12**	**6.65 ± 0.21**	**14.44 ± 0.94**	**2.17 ± 0.07**
M-10-1	6.08	5.39	33.20	40.51	5.90	24.80	4.20
M-10-2	3.57	3.41	26.00	31.68	7.50	21.50	2.87
M-10	**4.83 ± 1.77**	**4.40 ± 1.40**	**29.60 ± 5.09**	**36.10 ± 6.24**	**6.70 ± 1.13**	**23.15 ± 2.33**	**3.54 ± 0.95**
M-12-1	8.87	6.84	42.00	67.17	4.10	34.40	9.20
M-12-2	5.28	5.33	46.40	58.30	8.90	38.00	4.27
M-12	**7.07 ± 2.54**	**6.08 ± 1.07**	**44.20 ± 3.11**	**62.74 ± 6.27**	**6.50 ± 3.39**	**36.20 ± 2.55**	**6.73 ± 2.91**

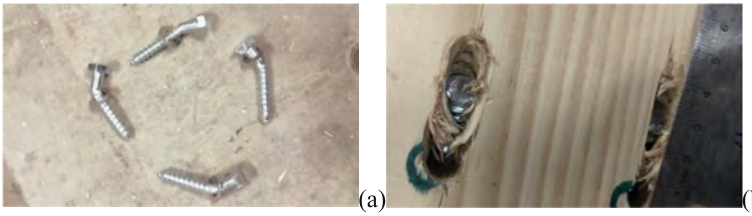
(a) (b)

Fig. 5. a) Screws developing a plastic hinge, b) extent of damage in timber.

4.2 Reuse Potential Tests

Figure 6 shows the load-slip curves for the specimens tested under the reuse potential protocol, which included ten loading-unloading cycles, followed by disassembly, reassembly with new screws and testing to failure. The cyclic part of the protocol is denoted with (I), and the post-reassembly part with (II). In all situations the secant stiffness of the first cycles was lower than that of the subsequent nine cycles. This is evidenced in by the average $k_{I0.4}$ versus $k_{I0.4'}$ in Table 2. The secant stiffnesses for the first cycle $k_{I0.4}$ were 4.15 kN/mm, 4.53 kN/mm and 5.98 kN/mm for the R-8, R-10, and R-12 specimens. The tenth cycle stiffnesses $k_{I0.4'}$ were 8.34 kN/mm, 9.28 kN/mm, and 12.13 kN/mm for R-8, R-10, and R-12 elements, respectively. Figure 8a shows that $k_{I0.4}$ enhances after the first cycle, and then is relatively constant.

After disassembly, it was observed that most screws were slightly bent, and had signs of wear, especially on their threads, making them hard to remove. The steel section was largely intact. Figure 7 shows a representative screw and panel after disassembly, indicating permanent deformations at the screw and some ovalisation of the panel hole. The diameter of the hole following the loading direction was around 9 mm for the 8 mm screw, suggesting limited damage during the loading and unloading cycles. This is captured by a small translation of the unloading branch of the cycles in Fig. 6.

The installation of new screws did not have a significant effect on the elastic behaviour of the shear connection. As depicted in Table 2, the secant stiffness $k_{II0.4}$ was within similar ranges to $k_{I0.4}$. For the R-8, R-10, and R-12 specimens, $k_{II0.4}$ was 17.3%, 16.8%,

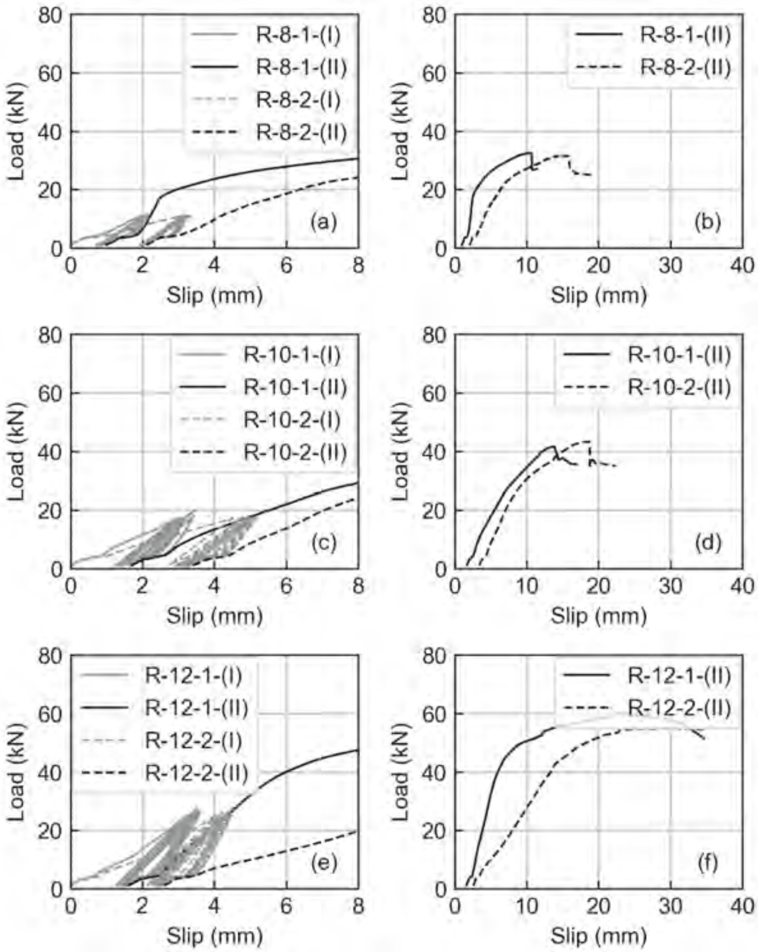

Fig. 6. Load-slip curves for: R-8 specimens a) cyclic tests (I), b) monotonic tests (II); R-10 specimens c) cyclic tests (I), d) monotonic tests (II); R-12 specimens e) cyclic tests (I), f) monotonic tests (II).

and 7.7% higher than $k_{I0.4}$. These values are within the standard deviation of the tests, thus can be considered insignificant. The $k_{II0.6}$ suggests similar observations. With regard to the strengths, for the R-8, R-10, and R-12 groups, the average F_y were 23.8 kN, 25.3 kN and 48.1 kN, respectively. For the same groups, the average F_{max} were 32.1 kN, 42.4 kN, and 57.9 kN, respectively. These values are similar to and within the standard deviation of those from the monotonic tests presented in Table 1.

It is shown that the disassembly and reassembly had minimal or no influence on the strength and stiffness, indicating full reusability of the CLT panels. With regard to ultimate displacement δ_u and slip ductility μ_δ, the differences between the samples under the monotonic tests and reuse potential tests are also rather minor. For M-8 $\mu_\delta = 2.2$, whilst for R-8 $\mu_\delta = 3.1$; for M-10 $\mu_\delta = 3.5$, whilst for R-10 $\mu_\delta = 3.5$; and for M-12 μ_δ

Table 2. Results from the reuse potential tests.

Specimen	$k_{I,0.4}$ (kN/mm)	$k_{I,0.4'}$ (kN/mm)	$k_{II,0.4}$ (kN/mm)	$k_{II,0.6}$ (kN/mm)	Fy (kN)	Fmax (kN)	δ_y (mm)	δ_u (mm)	μ_δ (-)
R-8-1	3.28	9.02	5.02	4.72	23.50	31.57	4.80	13.81	2.88
R-8-2	5.02	7.65	-	-	24.00	32.54	3.10	9.73	3.14
R-8	**4.15 ± 1.24**	**8.34 ± 0.97**	**5.02 ± 0.00**	**4.72 ± 0.00**	**23.75 ± 0.35**	**32.06 ± 0.69**	**3.95 ± 1.20**	**11.77 ± 2.88**	**3.01 ± 0.19**
R-10-1	5.50	9.68	5.48	5.00	23.50	41.49	3.95	15.24	3.86
R-10-2	3.57	8.89	5.42	5.11	27.00	43.21	4.81	15.10	3.14
R-10	**4.53 ± 1.36**	**9.28 ± 0.56**	**5.45 ± 0.04**	**5.06 ± 0.08**	**25.25 ± 2.47**	**42.35 ± 1.22**	**4.38 ± 0.61**	**15.17 ± 0.10**	**3.50 ± 0.51**
R-12-1	5.97	11.82	8.96	9.41	47.20	59.94	5.03	33.03	6.57
R-12-2	5.98	12.45	4.00	3.72	49.00	55.90	12.80	43.50	3.40
R-12	**5.98 ± 0.01**	**12.13 ± 0.45**	**6.48 ± 3.50**	**6.57 ± 4.03**	**48.10 ± 1.27**	**57.92 ± 2.86**	**8.92 ± 5.49**	**38.26 ± 7.40**	**4.98 ± 2.24**

= 6.7, whilst for R-12 $\mu_\delta = 5.0$. As for the other parameters, the difference in ductility parameters between the two sets of tests were within the standard deviation.

Considering the potential for reusing and recycling steel and timber in construction, it is apparent that the steel sections can be repurposed effectively. In this particular case, as there was no visible damage to the steel section, the same holes were used. However, other areas can be targeted for drilling, away from the previously used points, if needed.

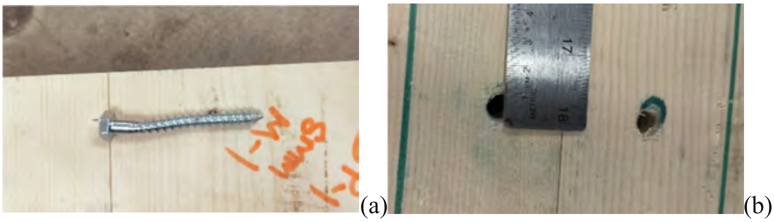

Fig. 7. Details after disassembly: a) deformed screw, b) timber hole ovalisation.

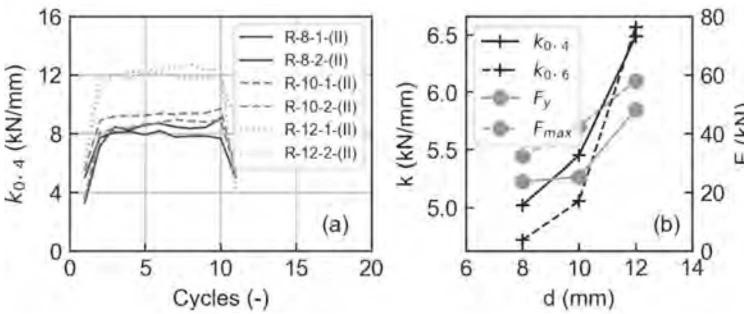

Fig. 8. a) Stiffness response of reuse potential test specimens, b) relationship between screw diameter versus stiffness and strength from the monotonic tests (II) for R specimens.

As for the CLT panels, they offer multiple ways for reuse. One option is to flip and interchange the panel sides, while another is to introduce screws at points more than 100 mm away from previous screw locations, as these would be far away from the damaged areas due to loading. From the test observations, it is worth noting that reusing the screws for different specimens is not possible as these had hinging and straightening would change the mechanical properties.

In lack of guidance for the evaluation of the reuse potential of steel-timber shear connection components, a procedure was adopted involving ten loading-unloading cycles to 40% of the failure load of the monotonic testing counterpart specimens. Although the loading regime is representative only for some in-service loading scenarios, the lower amplitude and higher number of cycles obtained from a probabilistic approach for the load distributions and changes during the design life of a building could be considered. The approach assumed only short-term loading, which does not include specific material effects such as creep in timber, which may change the overall structural response and CLT reuse potential.

The paper showed that dry connections using coach screws enable component disassembly of steel-timber hybrid systems at the end of life, rendering them circular. For quantification of reuse potential, a structural reuse index can be developed using quantitative information obtained from the testing, such as the relative stiffness between the reassembled and original specimen, the relative load-carrying capacity of the reassembled specimen and that tested under monotonic conditions, the permanent deformations in the removed screws, as well as qualitative parameters related to the user perception on the disassembly process. This index can be incorporated or correlated with typical circularity indicators for buildings.

5 Concluding Remarks

This paper evaluated the disassembly capability of steel-timber shear connections, tested under in-service cyclic loading, as well as their reassembly and structural reuse potential through testing. A detailed account of experiments involving double shear configurations with coach screws of three diameters (8, 10, 12 mm) was given. Monotonic tests were first carried out to evaluate the main mechanical response parameters. Counterparts were then tested under ten loading-unloading cycles to 40% of the capacity obtained from monotonic tests to evaluate stiffness degradation characteristics as well as specimen kinematics. After disassembly and measurements, the specimens were reassembled and tested to failure. The main remarks are outlined below.

The monotonic tests showed that the secant stiffnesses, yield and ultimate strengths, and slip ductility ratios increase with screw diameter, as expected. The 8 mm screws experienced a brittle failure at the interface between the smooth shank and the threaded shank, whilst CLT panel crushing or splitting was minimal. The 10 mm and 12 mm screws had a plastic hinge indicating ductile forms of failure.

The cyclic test observations indicated that the secant stiffness increased after the first cycle, and then was relatively constant to the tenth cycles for all specimens. After disassembly, all screws, regardless of their size, had permanent deformations, and the timber panel indicated limited damage during the loading-unloading cycles, in the range of 1 mm. The stiffness, strength and ductility of the reassembled specimens were similar to those from the monotonic tests.

The disassembly and reassembly had minimal or no influence on the strength and stiffness, indicating full reusability of the CLT panels. For quantification of the reuse potential, a structural reuse index can be developed using quantitative measurements from the tests. This index can then be incorporated or correlated with commonly used circularity indicators for buildings.

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Experimental Study on the Behaviour of Glulam Timber Beams Bonded with Glued-in BFRP Rods

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Abstract. The technique known as glued-in rods (GiR) presents an appealing option for effectively connecting structural timber members. The utilization of fibre reinforced polymer (FRP) rods offers additional advantages, such as reduced weight, improved corrosion resistance and lower thermal conductivity. Studies examining the behaviour of GiR connections with Basalt FRP (BFRP) rods are limited, and there is currently a lack of guidance for their fabrication and design. This paper presents an experimental study on the performance of glulam timber beams bonded with glued-in BFRP rods. Epoxy adhesive was used to glue the BFRP rods into the cross-sections of glulam, forming the connections. The experimental programme includes four types of connections, investigating two configurations for the glued-in rods (Designs D1 and D2) and two rod diameters (8 mm and 10 mm). Testing was conducted with four replicates for each connection type, resulting in a total of 16 tests. To assess the moment capacity of connections, a four-point bending set-up with a 2300 mm span, was applied. The response in terms of load-displacement response was monitored and the failure mechanisms were assessed. The predominant observed failure mode was bar pull-out and tensile splitting of timber. D1 connections with 10 mm bars demonstrated superior performance in both moment capacity and maximum displacement at failure.

Keywords: Glulam Timber Beams · BFRP · Four-Point Bending · Glued-in Rods

1 Introduction

Concerns about climate change, particularly the impact of carbon dioxide emissions, have led to increased global interest in the use of timber, owing to its sustainable properties. Timber has been employed in construction since ancient civilisation, due to its attractive aesthetics appearance, favourable strength-to-weight ratio, workability and toughness. Compared to natural timber, glued laminated (glulam) members have several advantages. The utilization of glulam can result in higher strength, as defects are distributed within the layers of the beam. However, forest depletion and the variability of natural timber makes the mass production of structural timber challenging. Addressing this challenge can be achieved, to some extent, by reusing existing timber sections.

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Joining sections of existing timber members allows for the production of new timber elements. Traditional timber connections, such as nailed or bolted connections, demand long machining times, substantial labour and are primarily suitable for smaller loads. Conversely, Glued-in rods (GiR) [1], are an effective method to connect timber sections, while offering several other advantages.

Previous investigations on glued-in rod connections have mainly focused on steel rods as connectors in the jointing system. The moisture content of natural timber makes the use of steel rods rather unfavourable as it is prone to corrosion penetration. The utilization of FRP rods offers additional advantages, such as reduced weight, improved corrosion resistance and lower thermal conductivity [2]. Research on the GiR technique with FRPs has recently been gaining momentum, but the main focus has been limited to Glass FRPs (GFRP), primarily due to its lower cost compared with carbon. Research on other FRP variants such as Basalt FRPs (BFRP), which offer relatively equivalent or even superior performance to GFRP considering the price, are very limited. Furthermore, despite the advantages of the GiR over conventional joint techniques, its incorporation into design is presently hindered by the lack of reliable design standards. To bridge these gaps, the current research focusses on examining the performance of glulam timber specimens joined with glued-in BFRP rods. The variables considered in the present research include the impact of the design types and rod diameter on the capacity of the timber samples. The test results provide a sound basis for formulating guidelines for the design of structural timber connections with GiR.

2 Experimental Study

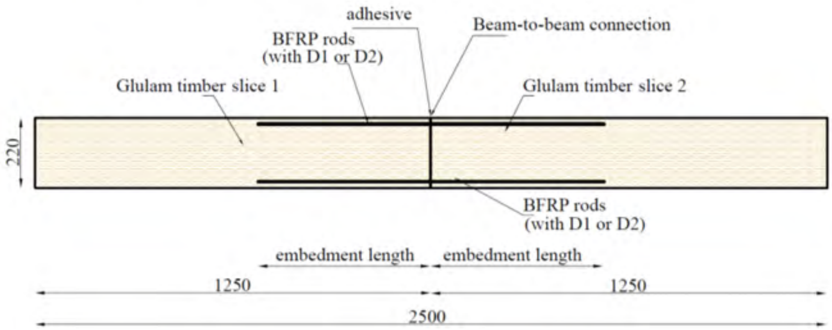
2.1 Materials

This study used glued laminated timber graded as GL28, with characteristic bending strength 28 N/mm^2. The BFRP rods used were supplied by Magmatech [3] from their RockBar range. These rods have an elastic modulus of 54,000 N/mm^2 and a tensile strength of 920 N/mm^2 [4]. Two diameters of BFRP rods were utilized, specifically 8 mm and 10 mm. Two-part epoxy adhesives, recognized for their excellent gap-filling properties, were employed. Supplied by Rotafix [5], these adhesives have a nominal shear strength of 12.5 N/mm^2.

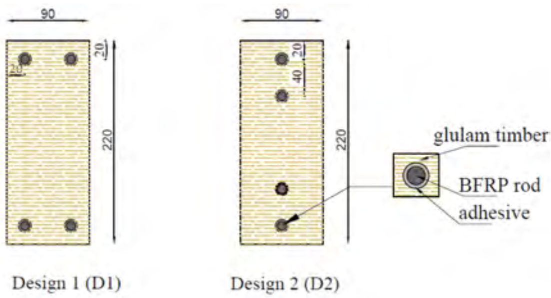
2.2 Glulam Bonded Specimens

Each glulam timber specimen had a total length of 2500 mm and was fabricated by joining two 1250 mm slices using glued-in rods. The timber specimens had nominal cross-section of 90 mm × 220 mm. The connection consisted of BFRP rods embedded through a length of 20 × rod diameter on either side (see Fig. 1a) and glued-in with epoxy-adhesive of 2 mm and 3 mm glueline thicknesses for the 10 mm and 8 mm rods, respectively. The rods were embedded in two different design configurations, D1 and

D2. Both configurations included two bars on the tension and two on the compression zone, but in D1 the bars were placed in the same horizontal line, whilst in D2 all four bars were in a vertical line (see Fig. 1b). For each of the rod arrangements, two rod diameters were investigated. Four replicates were examined for each connection type, leading to a total of 16 bonded specimens. The designation applied hereafter comprises the rod diameter, followed by the design configuration and finally the replicate number (see Table 1).



(a) Bonded specimen



(b) Cross section – design configurations (D1 and D2)

Fig. 1. Specimens with GiR connections (dimensions in mm).

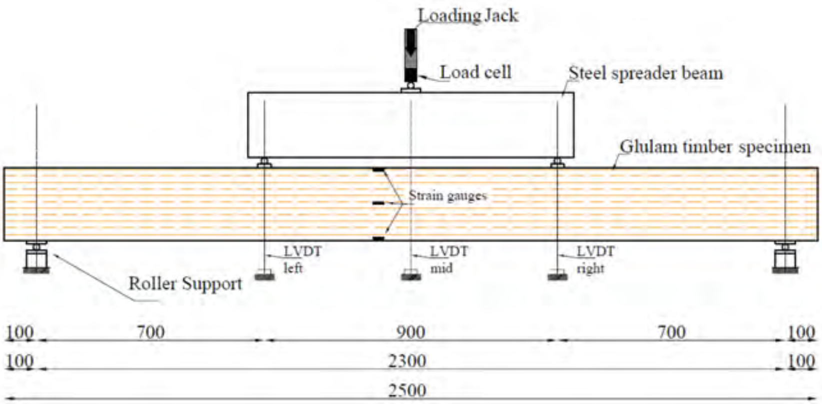
Table 1. List of specimens.

Rod Diameter (mm)	Configuration	Replicates	Designation
8	D1	4	8 - D1 - 1
			8 - D1 - 2
			8 - D1 - 3
			8 - D1 - 4
8	D2	4	8 - D2 - 1
			8 - D2 - 2
			8 - D2 - 3
			8 - D2 - 4
10	D1	4	10 - D1 - 1
			10 - D1 - 2
			10 - D1 - 3
			10 - D1 - 4
10	D2	4	10 - D2 - 1
			10 - D2 - 2
			10 - D2 - 3
			10 - D2 - 4

2.3 Testing

In order to investigate the moment capacity of the timber joints, a series of four-point bending tests with a 2300 mm span, were carried out. In Fig. 2, a photograph of the set-up and a schematic illustration are presented. Load transfer was facilitated through the use of an I-shaped steel stiffened spreader beam. Steel rollers, in conjunction with steel bearing plates, were employed at the support points. Three linear variable displacement transducers (LVDTs) were placed at the two load points and at mid-span to capture vertical displacements. To monitor the strain distribution profiles, strain gauges were affixed to the external faces of each specimen at three locations (see Fig. 2b). A data acquisition system was employed to record all necessary data during the testing process. The monotonic load was applied via displacement control with a constant rate of 3 mm/min [6].

(a) photograph of the set-up



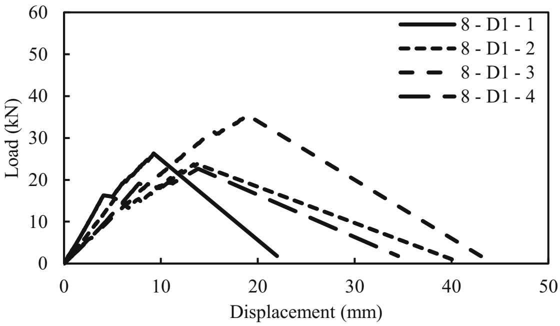
(b) schematic illustration of the set-up (dimensions in mm).

Fig. 2. Four-point bending test set-up.

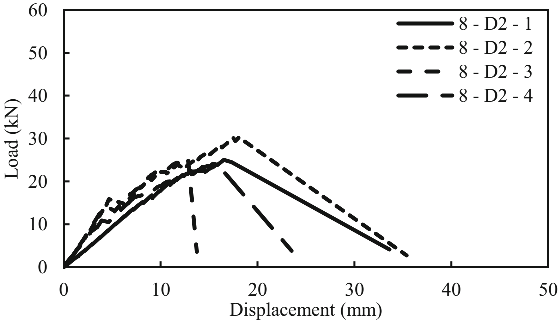
3 Results and Discussion

3.1 Load-Vertical Displacement Curves

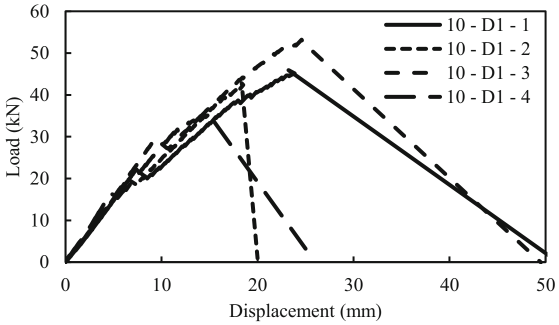
The curves depicting the load versus mid-span vertical displacement for all tests are recorded and presented in Fig. 3. Each graph shows the response of a group with similar characteristics. In most instances, a small "jump" in the load-displacement response, resulting in a slight alteration to the initial stiffness, was observed shortly after loading. The observed jump, corresponding to the moment a gap opening appeared on the connection interface, is attributed to the breaking of the thin layer of residual adhesive between the two timber slices (see Fig. 1a). In general, similar performance was observed from the four replicates within each group.



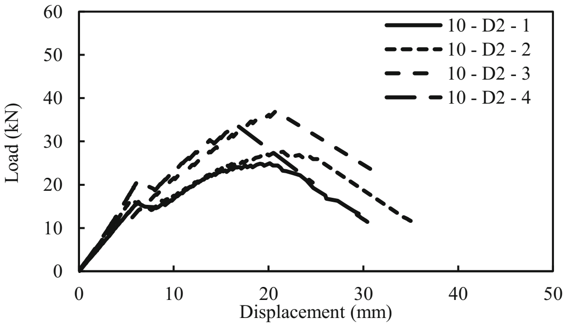
(a) 8 – D1 specimens



(b) 8 – D2 specimens



(c) 10 – D1 specimens



(d) 10 – D2 specimens

Fig. 3. Load-midspan vertical displacement curves for all specimens.

3.2 Failure Loads

Throughout the testing process, the applied load (N) was continuously monitored. The highest recorded value of the load is regarded as the failure load ($N_{u,Exp}$) of each specimen. To assess the moment resistance, the equation $M_{u,Exp} = (N_{u,Exp}/2) \times \alpha$ where α is the distance from the loading point to the support (700 mm in this case, as shown in Fig. 2b), was applied. Table 2 presents the failure loads ($N_{u,Exp}$), the moment resistance ($M_{u,Exp}$) and the corresponding mid-span vertical displacements ($\delta_{u,Exp}$).

Table 2. Test results at failure.

Specimen	$N_{u,Exp}$ (kN)	$M_{u,Exp}$ (kNm)	$\delta_{u,Exp}$ (mm)
8 - D1 - 1	26.30	9.21	12.69
8 - D1 - 2	23.76	8.32	13.74
8 - D1 - 3	35.37	12.38	19.30
8 - D1 - 4	22.64	7.92	13.85
8 - D2 - 1	25.02	8.76	16.53
8 - D2 - 2	30.26	10.59	18.10
8 - D2 - 3	25.58	8.95	12.65
8 - D2 - 4	24.35	8.52	15.72
10 - D1 - 1	45.91	16.07	23.23
10 - D1 - 2	42.78	14.97	18.36
10 - D1 - 3	53.20	18.62	24.58
10 - D1 - 4	35.33	12.37	14.88
10 - D2 - 1	24.96	8.74	20.14
10 - D2 - 2	27.62	9.67	21.53
10 - D2 - 3	37.07	12.97	20.79
10 - D2 - 4	33.80	11.83	16.68

3.3 Failure Modes

Typical cases of failure modes are shown in Fig. 4. The prevailing failure modes were bar pull-out with wood attached and tensile splitting of timber, signifying the integrity of the interface between the adhesive and the FRP rods.

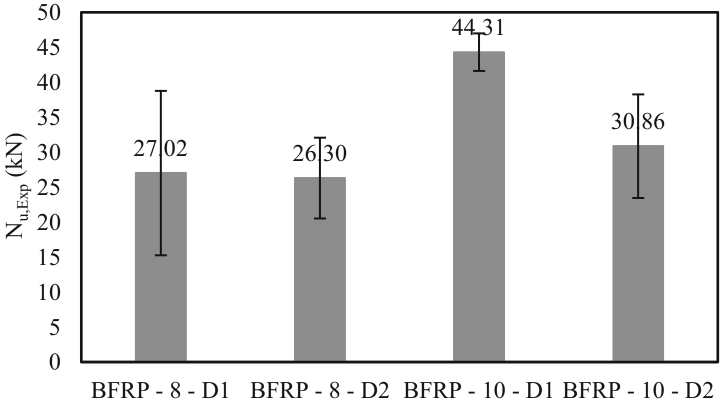
(a) 10 – D1 – 3: Debonding; splitting of timber along the bar at compression zone; splitting of timber at tension zone at soffit and size of beam

(b) 10 – D2 – 3: Debonding at the interface; pull-out of bars at tension zone; splitting at the soffit of the beam; splitting of timber at compression zone

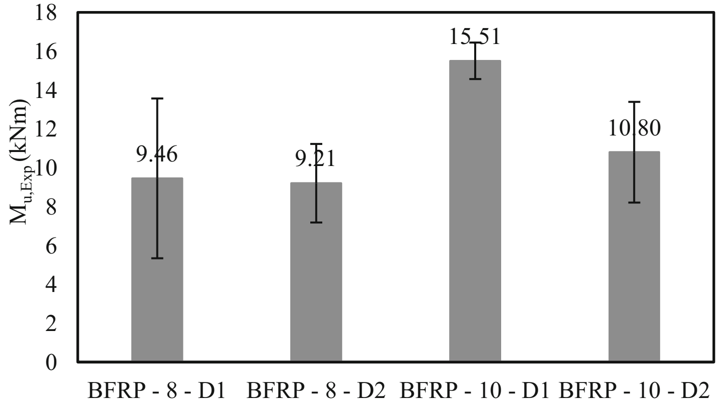
Fig. 4. Typical failure modes.

3.4 Comparison of Studied Cases

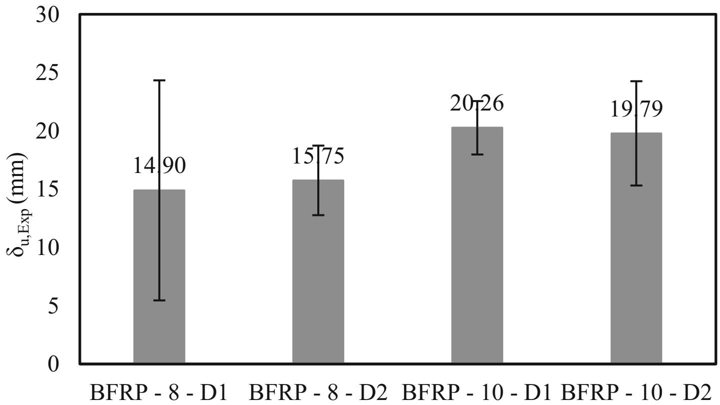
To allow visualization of the ultimate performance and comparison among the cases studied, Fig. 5 graphically depicts the average values of ultimate loads, moment resistance and corresponding displacements for each examined group of specimens. As evident, the bonded specimens with 10 mm rods and D1 exhibited the best performance both in terms of moment resistance and of corresponding displacement. Specifically, the joint with 10 mm rods and D1 attained an average ultimate load of 44.31 kN. As anticipated, for both D1 and D2, the joints with 10 mm rods surpassed their 8 mm rods counterparts. In particular, the average moment capacity for D1 increased by 64%, when comparing 10 mm to 8 mm rods. Furthermore, when comparing the two proposed designs, improved performance was observed for D1 design (i.e., four bars vertically) for both examined rods diameters (i.e., average $M_{u,Exp}$ equal to 9.46 kNm and 15.51 kNm for 8-D1 and 10-D1, respectively and average $M_{u,Exp}$ equal to 9.21 kNm and 10.80 kNm for 8-D2 and 10-D2, respectively).



(a) average ultimate load ($N_{u,Exp}$)



(b) average moment resistance ($M_{u,Exp}$)



(c) average displacement at ultimate load ($\delta_{u,Exp}$)

Fig. 5. Graphical presentations of average values for each studied group.

4 Conclusions

This paper presented an experimental study involving 16 bonded glulam beam specimens fabricated with glued-in BFRP rods. The key parameters investigated were the rod diameter (8 mm and 10 mm) and the design configurations (D1, D2). The load-displacement curves were reported and discussed. The predominant failure mode observed was pull-out of bars at tension zone and tensile splitting of timber. Across all cases, the connections with 10 mm bars demonstrated superior performance compared to those with 8 mm bars, with the D1 configuration outperforming configuration D2. Research work is currently underway to provide design guidance for the bonded glulam specimens. Future research could examine alternative design arrangements and comparison of their moment resistance with that of continuous beams and of other connection types.

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Experimental Study on the Feasibility of Disassembling and Reusing Lightweight Façade Wall Systems

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Abstract. This paper presents experimental investigations into the feasibility of disassembling and reusing exterior lightweight infill walls. The work stems as necessary steps towards the advancement of circular economy principles in future constructions. The experiment employed the single-shear test method commonly used to assess the shear strength of steel connections. The test samples consisted of cold-formed steel plates attached to hot-rolled steel plates, connected by screws. The cold-formed steel plate represents the track, a component of exterior lightweight infill walls, while the hot-rolled steel plate represents the beams of the primary structural frame. In total, twenty-one specimens were made: nine were tested after screwing, nine were tested after unscrewing and re-screwing, and three were tested after unscrewing, re-screwing, unscrewing, and re-screwing. The unscrewing step demonstrates the disassembly of the infill walls, while the re-screwing demonstrates their reuse. The experimental results revealed that the average peak strengths of the samples with different connections exhibited negligible differences. This can be attributed to the interaction between the screws and the connected cold-formed steel and hot-rolled steel plates, a mechanism further discussed in this paper. The test outcomes imply that exterior lightweight infill walls can be disassembled from the primary structural frame's beams after the infill walls' service life, and subsequently reused in the construction of other exterior lightweight infill walls. The study also demonstrated that more specimens should be tested to confirm the observation.

Keywords: Building science · Lightweight Structures · Reuse · Design for Disassembly · Cold-Formed Steel · Experiment

1 Introduction

The construction of building façades in the UK has increasingly used exterior lightweight infill walls (see Fig. 1), due to their lightness which enables quick construction, and thanks to their capacity to be easily integrated with a large range of insulations and finishing to achieve the required thermal performance and aesthetic look. The walls are often replaced every 30 years during building refurbishment for space adaptation,

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energy efficiency compliance, or humidity control [1, 2], despite their potential for longer use. The removed wall components are often sent to landfills or energy-intensive recycling processes, which contribute to some detrimental environmental impacts, such as carbon emissions and resource depletion. In fact, the frequent replacement of walls leads to a significant contribution to carbon emissions from these walls (more than 20% of the building's total embodied carbon). Although past efforts targeted recycling to improve the material use of these components, significant improvements remain difficult to achieve. Presently, circular practices of reuse for these components are lacking [3]. To address this issue, the authors have studied the disassembly potential for future reuse of components of exterior lightweight infill walls, focusing on lightweight cold-formed steel (CFS) members in previous research [4]. This study further explores the overlooked potential of disassembling and reusing the exterior lightweight infill wall itself by focusing on the screwed connections between the wall and the beam. Screwed connections in CFS systems has been largely studied to understand their shear behavior [5–7], but no work has been previously done to understand whether they could be safely removed and then reused again. This is what this paper starts to address. Connections' behavior is, indeed, critical for the possibility of disassembling and reusing any construction system, as also reviewed in Kitayama & Iuorio, 2023 [8]. The work presented in this paper is based on a set of experiments conducted in the George Earle testing laboratory at the University of Leeds. The experiment was conducted during March-April 2023. Readers may also refer to the relevant recent study [9] by the authors that investigated the potential of disassembly and reuse of gypsum plaster boards, another key component of the exterior lightweight infill walls, based on the literature survey.

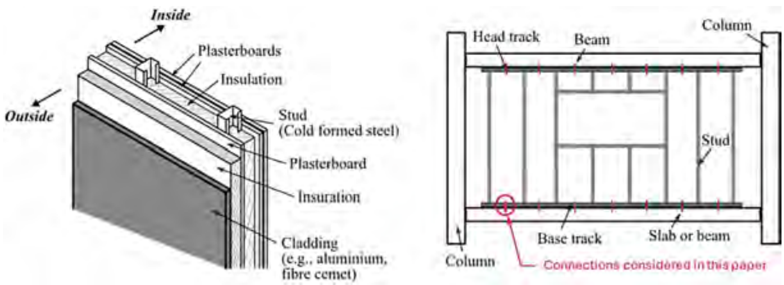

Fig. 1. Exterior infill wall: (left) notations of infill wall components; (right) notations of lightweight cold-formed steel members and surrounding primary structure.

2 Experiment

2.1 Preparation

CFS tracks of Grade S390 galvanized with Z275 zinc coating and hot-rolled steel (HRS) plates of Grade S355 (uncoated) were used for the experiment. The CFS tracks were cut to a length of 235 mm and the HRS plates were cut to a length of 250 mm. The CFS and

HRS plates were connected using Hex Head self-drill screws with 5.5 mm diameter and 40 mm length. Figure 2 shows the geometry of the specimen. Table 1 shows the cases of specimens and how they were tested.

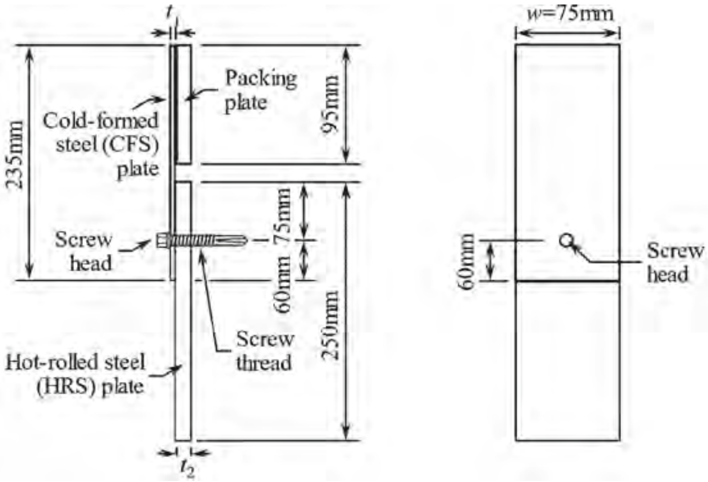

Fig. 2. Geometries of the tested specimens.

Table 1. Table captions should be placed above the tables.

Thickness CFS t_1 (mm)	Thickness HRS t_2 (mm)	Connection	Number of test
1.6	15	Screw → Test	3
1.6	15	Screw → Unscrew → Screw → Test	3
1.6	15	Screw → Unscrew → Screw → Unscrew → Screw → Test	3
1.6	10	Screw → Test	3
1.6	10	Screw → Unscrew → Screw → Test	3
2.0	15	Screw → Test	3
2.0	15	Screw → Unscrew → Screw → Test	3

As shown in Table 1, different thicknesses of CFS and HRS plates were used (1.6 mm or 2.0 mm for CFS plates; 10 mm or 15 mm for HRS plates). Seven different cases were considered. The case "Screw → Test" demonstrates the installation of walls and use. The case "Screw → Unscrew → Screw → Test" demonstrates the installation of walls, disassembly of the wall, subsequently re-install the wall and use. The case "Screw → Unscrew → Screw → Unscrew → Screw → Test" demonstrates the installation of walls, disassembly of the wall, re-installation the wall, disassembly of the wall, re-installation of the wall and use. Each case was tested three times with three different specimens with the same geometry to study the average behaviour of the connections.

Figure 3 shows the method of opening holes on the CFS and HRS plates. Note that the colour of the edge of the CFS plate (dark brown) is different from other part (silver). This is because the zinc coating of the edge of the CFS plate (about 10 cm in length) was removed using acid to measure the thickness of the CFS plates without zinc coating. The thickness of the zinc coating on the 1.6 mm CFS plates was 0.033 mm and that on the 2.0 mm CFS plates was 0.256 mm.

Fig. 3. Tested specimen preparation.

Figure 4 shows the photo of experiment of one of the cases listed in Table 1. A 600 kN Instron 5989 testing machine was used to perform the tests for the specimens to be pulled in tension and the screw is subjected to shear force. The test was conducted in displacement control (1 mm/min) and the data were collected every 0.5 s.

Fig. 4. Experiment of screwed connection (single-shear test method).

2.2 Results

The results of the tests are shown in Figs. 5, 6 and 7 for the specimens with 1.6 mm CFS and 15 mm HRS, 1.6 mm CFS and 10 mm HRS, and 2.0 mm CFS and 20 mm HRS, respectively. Figures 5 and 6 indicate that the unscrew and re-screw may cause slight reductions in the strength of the connection while Fig. 7 indicates that the same process may cause a slight increase in connection strength. Regardless of the reduction or increase in strength, the difference before and after the unscrew and re-screw processes did not cause notable differences in the observed strength values.

Figure 8 shows the photos of a failed specimen after the test. As seen in the photos, the failure occurred in shear in the screw at the intersection between the CFS and HRS plates. All the tested specimens showed the same failure mode.

Figure 9 presents the relationship between imposed displacement and the resultant force (strength) of the connection for specimen with 1.6 mm CFS and 15 mm HRS plates and for the case "Screw → Unscrew → Screw → Unscrew → Screw → Test". It shows that there is notable variability between the results of the three curves and indicates that the number of tests should be increased to obtain reliable observations.

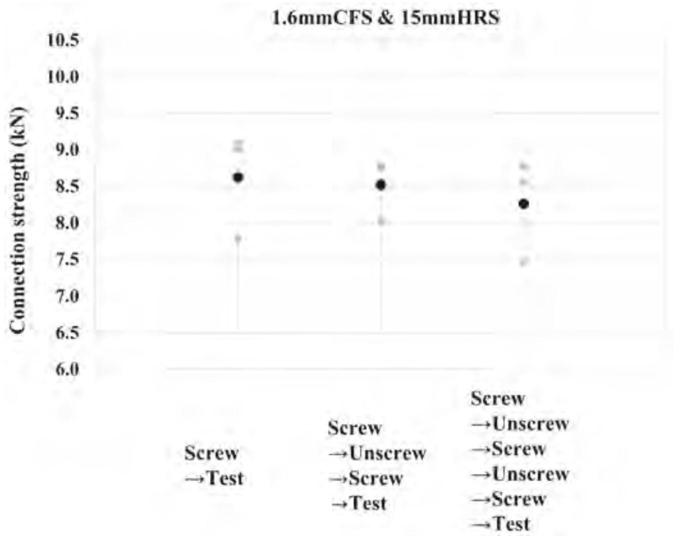

Fig. 5. Connection strength for specimen with 1.6 mm CFS plate and 15 mm HRS plate. The average of the three tests was indicated by large black dots. Individual test results were indicated by small grey dots.

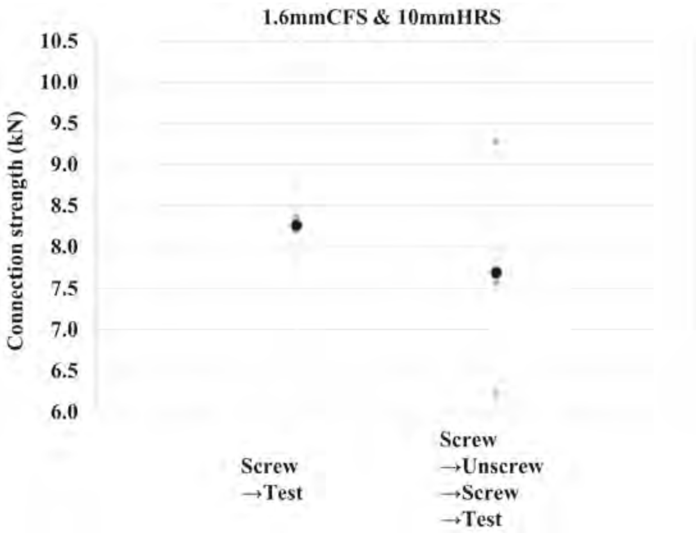

Fig. 6. Connection strength for specimen with 1.6 mm CFS plate and 10 mm HRS plate. The average of the three tests was indicated by large black dots. Individual test results were indicated by small grey dots.

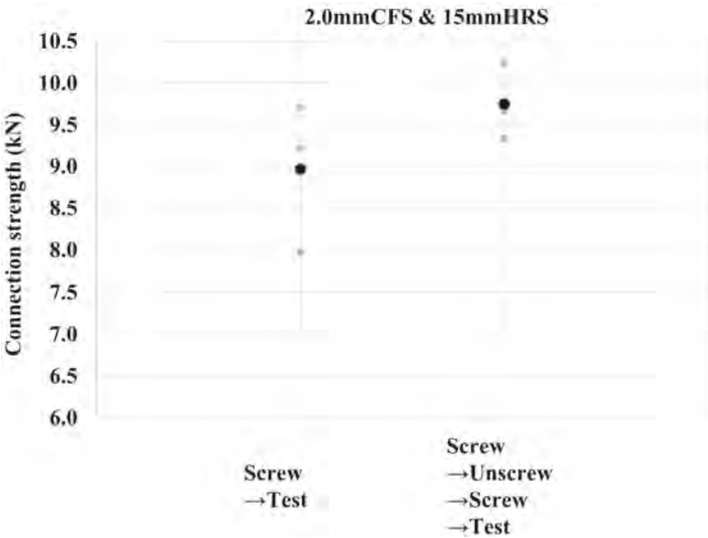

Fig. 7. Connection strength for specimen with 2.0 mm CFS plate and 20 mm HRS plate. The average of the three tests was indicated by large black dots. Individual test results were indicated by small grey dots.

Fig. 8. Failed connection after test.

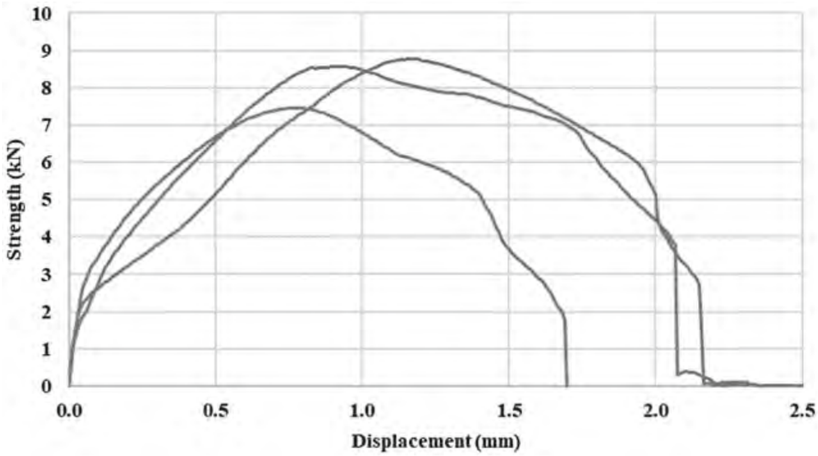

Fig. 9. Three test results from "Screw → Unscrew → Screw → Unscrew → Screw → Test" with 1.6 mm CFS and 15 mm HRS plates.

3 Conclusion

This paper presented an experimental study that investigated the feasibility of disassembling and reusing the exterior lightweight infill walls. The experiment focused on the connection between a typical steel member and a cold-formed steel plate representing the track of an infill wall and a hot-rolled plate representing a typical steel beam. To consider disassembly and reuse, the installed screws were unscrewed and re-screwed to the connection. It was observed that the process "Screw → Unscrew → …" tended to change the strength of connection negligibly. This indicated that there is a high potential for disassembly and reuse of the exterior lightweight infill walls. To confirm the observations from this study, further experimental work with more specimens would be necessary.

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Design for Deconstruction Through Digital Fabrication of Thin Spatial Systems

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Abstract. Spatial systems like shells, arches and shelters can often be used as temporary structures to accommodate short to medium expositions, events, or emergencies. This has historically allowed them to be designed for multiple uses. Recent advancements in computer graphics, algorithmic design, and advanced manufacturing have accelerated their development and opened new scope for applications, by exploiting new capabilities and opportunities for material-efficient designs and constructions. The authors aim to develop combined systems approaches to the design of resilient, de-constructible constructions for the built environment. This work presents the recent advancements in the development of discrete shell systems developed at the AS_Lab between the Politecnico di Milan and the University of Leeds, using biogenic materials such as wood which are inherently sustainable. Coupling geometry design and segmentation with ad-hoc connection systems, demountable systems have been developed, which are materially efficient, digitally designed, and fabricated, and can, in some instances, be robotically assembled. The study presents the conceptual design and fabrication of three prototypes, which have been realized to accelerate the transition to industry 4.0 while posing the focus on a circular future.

Keywords: Circular economy · design for deconstruction · computational design · Digital fabrication · lightweight structures · robotic assembly

1 Introduction

The continued increase of material resources' environmental and economic costs has brought attention to improving the reuse of our built environment. In this context, circular economy principles have been developed. Cities can lessen the detrimental effects of the urban built environment by using circular principles, which guarantee that materials and components are preserved and retained at their best value over multiple life cycles.

Computational design and fabrication methods, with special regard to additive and subtractive manufacturing, and robotic assembling are technologies that can be used to improve the circularity of the built environment. A large body of knowledge is under development to demonstrate this, and this paper, indeed, builds on this evidence. This paper demonstrates how digital design, advanced manufacturing, and robotic assembly

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can facilitate the development of de-constructible systems for curved surfaces, looking at three prototypes developed by Iuorio's group, in response to international collective exhibitions.

2 Methodology

The current study is intended to demonstrate the scope of design for disassembly in lightweight structural systems, particularly thin timber structures. By collecting a selection of our recent developments in this field, we exhibit some advancements in computational design, digital fabrication and assembly processes. These additions to the state of the art are shown to have potential to decrease material waste production, and allow for non-adhesive reversible connections which benefit the return of materials to construction stocks.

To demonstrate these contributions, Sect. 3 presents 3 case studies in the computational design of the ECHO shell, the ECHO arch, and the "Set in transition" prototype. Section 4 describes the use of digital fabrication technologies to manufacture elements of these designs, and the benefits of using these technologies. Section 5 describes some advancement in the use of robotic assembly for the construction of these new structural designs. Finally, conclusions are made highlighting the contributions, and how they bridge the gap between circular economy theory and practical applications.

3 Case Studies in the Design of Thin Spatial Systems

3.1 The ECHO Shell

The ECHO shell is a lightweight segmented shell system comprising of hexagonal wooden panels joined together with location-specific 3D printed connections [1]. The design of the ECHO shell revolved around dimensional constraints of the constructed prototype, imposed by a competition organized for the 60th Anniversary Symposium of the International Association for Shell and Spatial Structures in 2019 in Barcelona. However, the most critical limitations were practical ones and were imposed by manufacturing and shipping considerations e.g. limit on the maximum size of panels for manufacturing purposes, weight of the structure for shipping purposes, and the necessity to assemble and disassembling it.

The labour-intensive nature of shell construction and assembly was a starting point of consideration in the development of the ECHO shell. The goal was to design a structure that can be assembled and most importantly safely disassembled by a team of 2 to 4 people in a few hours. The shell was designed to support self-weight-induced internal forces. A 6 mm poplar plywood material was shown to be suitably lightweight and structurally sufficient to withstand the expected forces while fulfilling manufacturing requirements i.e. being suitable for laser cutting.

The entire design was contained in one parametric definition, which helped streamline the eventual changes in later stages. Starting with a simple concept of a hemispherical synclastic shape, that represents a portion of a soundwave, which inspired the name ECHO. Then moving into a segmentation process or "Tessellation" that generates the hexagonal panels on the curved surface (Fig. 1). And finally generating a planarized version of each individual panel in a process called "Planarization" that converts the original surface into a continuous curved poly-surface of planar panels, while maintaining the original properties of a shell that converts the external forces into membrane actions [3].

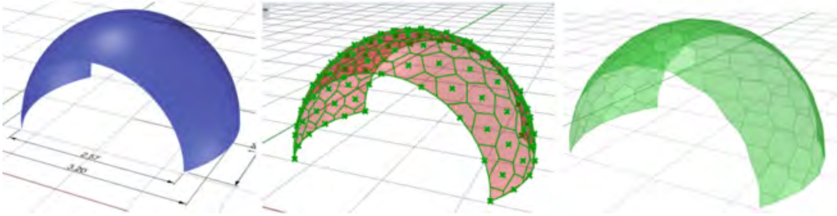

Fig. 1. Concept, tessellation, and planarization of the ECHO shell made with Grasshopper environment [2].

A multitude of steps follow; generating finger joints between the panels that help with assembly and positioning, generating final features of the panels that create slots for the 3D printed connection, panel numbering, and generating and exporing manufacturable panels.

Fig. 2. The ECHO shell during construction. The panels require some external support during assembly, to counteract bending moments; however, support can be removed after assembly.

The design achieved its purposes not only by producing a stable structure, but most importantly by resulting in a structure that has - so far - been assembled and disassembled three times for testing, presenting, and educational purposes, the last of which was for the Leeds International Summer School in 2022 where a group of students managed to reassemble the structure under supervision (Fig. 2). The design has also shown to be durable with very few maintenance requirements or inappropriate storage conditions, while maintaining the same level of structural stability and having minimal need for support in the construction and deconstruction stages.

3.2 The ECHO Arch

Since the original ECHO shell concept, developing anticlastic surfaces was deemed to complete the sound echo waves blend with shell curvature. Hence, to demonstrate the capacity of the conceived system, an arch was designed to follow the same principal design and fabrication methodology of the shell, while relying more on the catenary load-resisting mechanism. The arch was assembled, in his final configuration at the Material Eco-Systems symposium, organized by Iuorio for the Venice Biennale of Architecture, Italy in 2023 (Fig. 3). The assembly, disassembly requirements and being flat packed for shipping were essential in this design.

Fig. 3. The ECHO arch as displayed at the "Material Ecosystem Symposium" within the Collateral Event at the Venice Biennale of Architecture 2023.

The design starts with a catenary arch as a starting surface; however, the planarization process results in a poly-surface that deviates from the original. The original surface is - by design - a catenary arch, but the final surface, combined with the very thin panels, results in forces that do not follow the optimal flow path of forces of a catenary. This introduces bending moments that are most pronounced in the nodes of the panels, in other words, in the connections.

The arch demonstrates that even deviating from the optimal shape of a catenary, the arch, realized with thin and flexible materials, could withstand static and dynamic loading. The deviation from catenary and the consequent resulting forces could be counteracted by creating more rigid structures and, hence, requiring more material usage. However, an appropriate design of a connecting system can resist bending moments while maintaining the structural stability of the structure, avoiding increased material usage, and minimizing the supports needed in the construction stages, as demonstrated by this prototype.

3.3 Set in Transition Leaf

In addition to using external joints to constrain panels, other research within the group has focused on the design of self-supporting shell structures with integral joints. Such designs have made use of dovetail inspired joints cut from the panel material, using geometric Boolean operations to remove and add matching joints and slots through a design (see Fig. 4). Such designs are driven by traditional joinery and depend on friction-based interference fitting. The use of integrally attached joints has the benefit of reducing internal stress on panels at interfaces, due to bending moments that may arise. The use of the joints additionally allows for dry stacking assembly, that is, without adhesives or external fixings, making deconstruction trivial.

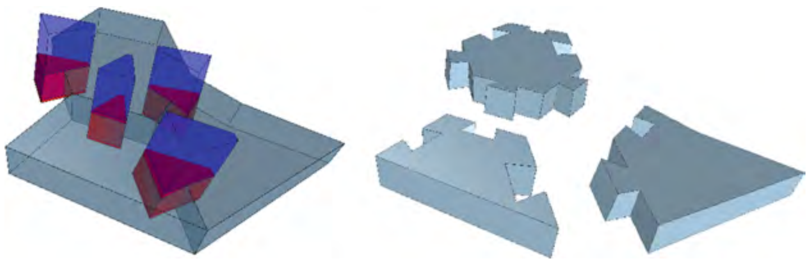

Fig. 4. A selection of three neighbouring panels, showing the boolean addition (red) and subtraction (blue) of dovetail wedges from pairs of panels, giving panels with integral mating joints. Wedges are extruded along the perpendicular vector of the planar panels.

An additional key driver of this work was to develop a system that could be self-supporting not only once assembled but also during assembly. Formwork makes up a large percentage of construction waste for shell structures, estimated by some to be as high as 45% of carbon emissions in constructing a shell [4]. By designing assemblies that can support themselves during construction, this formwork waste can be mitigated, providing a more sustainable construction approach.

In order to model structural stability during assembly, the coupled rigid block analysis was utilized. Using scale 3D printed models, and assuming that the shell can be treated as a set of rigid panels, the use of the analysis was validated by comparing to replica models, demonstrating the use of stability tools other than FEA for rapid, early stage design feedback [5]. It was shown that with suitably low tolerance on dovetail joints, long cantilevered sections could be constructed, unsupported, depending on friction effects on joints to maintain stability throughout assembly.

We received an invitation to propose a physical model to be displayed at the Students as Researchers exhibit for the Biennale di Architettura in Venice 2023, which aimed to discuss how schools of architecture and architectural engineering are responding to the global challenges brought by climate change and social needs. For this, a protype titled "Set in Transition" was developed. The prototype aimed to demonstrate the necessity of reducing our built environment footprint by developing systems using geometry and advanced static to reduce material use in the final product and during construction, that can be adopted over multiple cycles. A maple leaf inspired design was specified and hand drawn before being converted into a computer graphics representation, and form-finding was applied to the free-form drawing, by anchoring the base artificially and using energy goals to pull regions of the geometry around, whilst maintaining a funicular form which is dominated by membrane loading. The surface was segmented, and planarized using the variational tangent plane intersection method [6]. Using the CRA technique, the leaf was designed to be stable throughout assembly at a full scale of 2 × 2 × 1 m; for the purpose of the exhibition, a scale version was manufactured to fit within a 0.7 × 0.7 × 0.35 m envelope (Fig. 5).

Fig. 5. The "Set in Transition" interlocking leaf structure. Each panel element is inserted along the vector perpendicular to its own plane.

4 Technological Advancements in Digital Fabrication

4.1 Additive Manufacturing

Advancements in 3D printing technologies and the availability of 3D printers have made creating custom parts with very specific dimensions and features more accessible than ever. A novel connection system was created for the ECHO shell that relies on pins on location-specific connections that pair in a friction-fit manner with slots in the panels (Fig. 6). Each connection consists of two components joint together by a small fastener. The two components of the connection join three adjacent panels for the shell system, and then adapted to join two panels for the ECHO Arch.

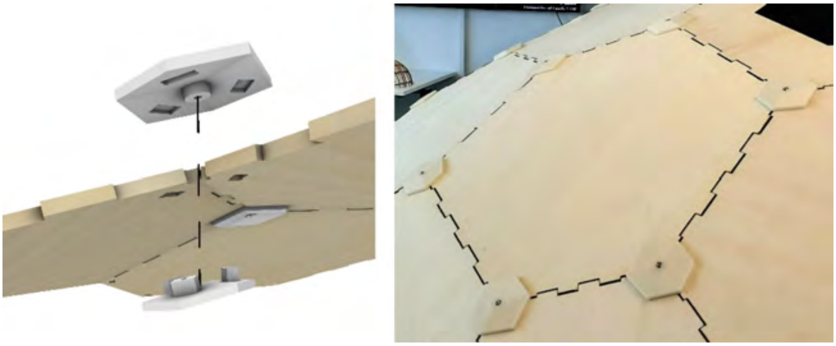

Fig. 6. Parametrically designed, 3D printed connections for the ECHO shell and arch. Printed from PLA plastic, the top and bottom parts are fastened together to constrain the 6 mm thick plywood panels.

4.2 Laser Cutting

Laser cutting is a subtractive manufacturing technique that can be very efficient in material use if the sections to be manufactured were optimized to the size of the sheets of raw material used. Laser cutting was used to manufacture the panels for all of the reviewed projects. Laser cutting integrates well with the design to manufacturing methodology followed, because as a Computer Numerical Control (CNC) manufacturing method, it uses vector images that can be very easily extracted from the design.

4.3 Approximating Complexity: Stacked Contour Method

While laser cutting can be utilised to manufacture single layer panels, it can also be used for the creation of thicker, more complex geometries. The construction elements within the Set in Transition leaf, along with other panels being tested within our lab, use a combination of positive and negative gradients on their interface surfaces to create the required cantilevering and joining effect. Initially, 5-axis CNC milling was considered for the manufacture of these components, however the cost proved to be inhibitive.

By instead slicing panels into layers within parametric design software Grasshopper [2], it is possible to approximate them by laser cutting them as laminar layers which can then be reconstructed (Fig. 7). Some details are lost on the edges due to the approximation, although this effect can be reduced by using thinner layers of sheet material.

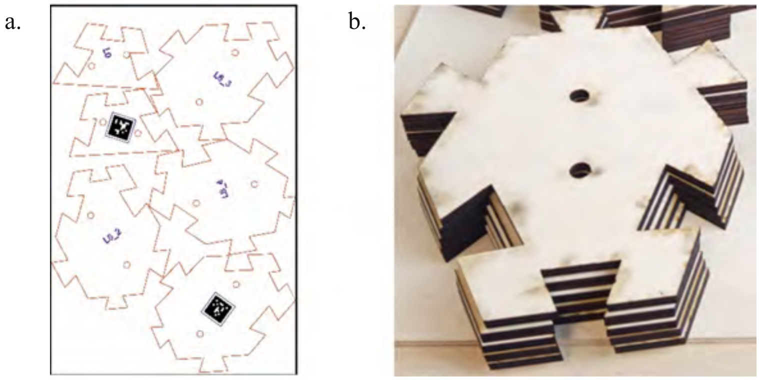

Fig. 7. The method of stacked contours used with laser cut sheets. a) A laser cutting sheet for a selection of panel layers. b) A single panel, made of 6 mm timber sheets.

The use of sheet material allows for reduction of material waste by finding tight nesting of panel borders within a sheet. Assessing the no-fit polygon criteria [7] to find feasible, non-overlapping configurations of panel boundaries, different layouts of panels can be found in an attempt to minimise the offcut area. For the example sheet of Fig. 7, with dimensions 40 × 60 cm, an area of 1,030 cm^2 is offcut representing 43% material wastage; this can be further reduced by having a larger selection of panels to place to fill spaces. It should be noted that this is still a significantly lower level of waste than produced by CNC milling, particularly as the offcuts can be reused as compared to milled material. Panels can also be disassembled by removing their reference dowels, allowing them to be reintroduced to the material stock with a small amount of sanding to post-process.

5 Robotic Assembly

The use of robots in construction of the built environment will likely continue to grow and disrupt the AEC industry, with 81% of firms planning to introduce robotics in the next 10 years according to a survey by robotics company ABB [8]. While digital fabrication can aid the reduction of material usage, innovative assembly systems can additionally reduce the dependence on human operatives, improving safety in construction. Further, the use of digitally controlled assembly agents and sensing can allow for better recording of process data for construction monitoring, giving live feedback on the assembly.

Our lab has explored the use of a robot manipulator arm for the assembly of the thicker, stacked contour panel system. Making use of custom-made gripper fingers, the arm can hold onto the dowel referencing rods securely. QR code style Apriltags [9] are used to monitor the construction environment and inform the robot where to pick and place panels, shown in the center of panels in Fig. 8, while the panel placement is informed by the reach envelope of the particular robot.

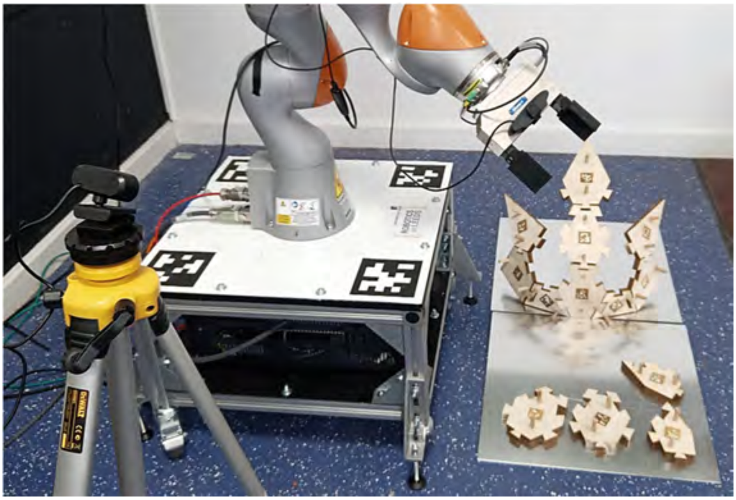

Fig. 8. Robotic assembly of the leaf panels.

The use of robot arms for assembly additionally requires encoding the relative insertion directions by which panels can be connected to each other, which a human operative would implicitly understand. Using custom Grasshopper C# components, structures can be represented as a tree structure, where nodes represent panels, and edges represent the liaisons between them and their relative insertion vectors [10], found from the mating geometry. We demonstrated that, through such a representation of a structure, potential assembly sequences could be found algorithmically, finding multiple potential assembly sequences which can then be checked to find the most structurally stable sequence, and by extension, a suitable stable sequence for disassembly. This area could certainly be extended for better planning of disassembly in end-of-life decommissioning of buildings, where BIM or CAD data is available.

6 Conclusions

Digital techniques can be of support in the transition to circular future. Material and component passports, digitally driven geometries for efficient use of material, scanning technologies for construction tracking, and advanced manufacturing with subtracting and additive manufacturing to build only what needed where needed can be implemented to develop de-constructible systems. The research presented in this paper, using as case study shell design and fabrication, demonstrates how the development of discrete systems with ad-hoc connections, can facilitate the reusability of components and full systems. It also demonstrates the importance of considering the construction and future de-construction process in the initial stages of the design process, to reduce the amount of material, and increase the amount that can be recovered. It finally builds on the idea that strength can be achieved through geometrical efficiency, and in this sense digital manufacturing techniques can drastically facilitate that. These results open the way to large scale experiments, that will integrate materials and components retrieved from existing buildings.

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Use of Textile Fiber Waste to Improve the Thermal and Mechanical Performance of Cement-Based Mortar

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Abstract. Improving the thermal properties of materials used in buildings is crucial to reducing energy demand and consumption. This study investigated the use of textile fiber waste in cement-based composites for construction applications. Mechanical and thermal characterizations were carried out to assess the behavior of cement mortars with different percentages of two types of textile fibers after 7 and 28 days of water hardening. The results show that the incorporation of fibers can significantly improve the thermal insulation capacity of buildings by reducing the thermal conductivity of cement mortar by up to 52%. In addition, the use of textile fibers can improve the mechanical strength of the cement mortar, especially with a high fiber content and a longer curing time.

Keywords: Textile fiber · Cement mortar · Thermal insulation · Experimental study · Building applications · Mechanical performance

1 Introduction

The energy demand in buildings is currently increasing steadily. According to the International Energy Agency (IEA), buildings are responsible for more than 30% of global energy consumption and 27% of total emissions [1]. A significant portion of this energy use and associated emissions is attributed to the need to condition spaces to maintain thermal comfort [2]. The intensity of heat exchange with the outside environment and the thermal conductivity of building materials play a crucial role in determining the energy required for space conditioning. To counteract heat loss, the incorporation of fibers into building materials has proven to be an effective solution for reducing thermal conductivity [3]. Many researchers have studied the effects of adding fibers to cement mortar as a thermal reinforcement material, including banana fiber [4], coir scraps [5], acai [6], coconut fiber [7], and rice straw fiber [8].

Textile Reinforced Mortar (TRM) is a fiber-reinforced cementitious compound and is considered a promising material owing to the exceptional characteristics of textile fibers. However, based on a literature review, the use of textile-reinforced mortar was

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restricted to certain applications. Fabric mesh and textile yarn have been employed to improve the tensile strength, ductility, and durability of cementitious composites in general [9–18]. However, there is a research gap in the application of textile fibers, such as spinning waste, as thermal reinforcement material in cement-based composites. Oliveira et al. [19] studied the use of fabric shavings in cement mortar and reported that the inclusion of fabric yarn resulted in a decrease in the mechanical performance of the cement mortar, with the exception of bond strength. In addition, a thermal test of the fabric yarn mortar at 60 °C showed a temperature difference of 12 °C between the inner surface and the reference surface due to the porosity. Other researchers [20] also examined the integration of textiles in construction applications and found that increasing the textile content improved the thermal stability of the cement mortar.

The aim of this study is to create a novel building material with low thermal conductivity by integrating two types of textile waste into a cement-based mortar. The study involved the creation of various textile fiber-reinforced composites by substituting sand in the cement mortar with different proportions of fiber waste. The resulting reinforced mortars were then subjected to mechanical and thermal characterization. If the incorporation of textile fiber waste into the cement slurry leads to standard-compliant properties, this could prove to be a promising solution for reducing the environmental impact of the textile and clothing industry.

2 Materials and Methods

2.1 Materials and Sample Preparation

Portland cement CEM I/52.5 according to standard EN-197-1 [21] was used to produce the cement mortars. Natural sand AF-R-0/2-S was used as a fine aggregate. Two types of textile fibers were included as reinforcement materials, which were disposed of as waste at the end of the textile spinning process. Type I textiles consisted of linen, cotton, and polyester fibers, while Type II consisted of only cotton fibers. The fibers were dispersed by blowing in compressed air before adding them to the mixture. Textile fiber-reinforced cementitious composites were prepared by replacing the sand in the mortar at 10%, 20%, 30%, and 40% volume fractions of one of the two types of textile. All mixtures were prepared according to the terminology of standard EN 1015-2 [22] as fully described in [23]. Some of the prepared samples (Fig. 1) were cured in water for 7 days while the others stayed for 28 days.

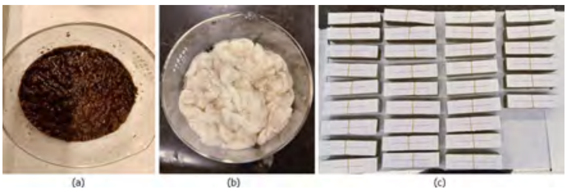

Fig. 1. (a) Type I-textile fibers; (b) Type II-textile fibers; (c) Textile-reinforced mortars after water curing.

2.2 Samples Characterization Methodology

The fresh and cured state of the cement-based composites were tested for bulk density according to the European standards EN 1015-6 [24] and EN 1015-10 [25], respectively. To evaluate the mechanical properties of the cured cementitious composites, flexural and compressive strength tests according to the EN 1015-11 [26] standard were carried out using a COINSA Controls Industrial double-head machine. The three-point bending test was performed on each specimen at a load rate of 50 ± 10 N/s, followed by a compressive strength test on one of the two resulting fragments at a load rate of 2400 ± 200 N/s. In addition, the TEMPOS thermal property analyzer was used to perform thermal conductivity characterization. A probe consisting of a needle with a built-in heating element and temperature sensor was used to measure thermal conductivity based on a transient line heat source method. In fact, an electrical current is passed through the heater and the temperature change of the sensor is measured over time [27]. The thermal conductivity of each mortar was determined by analyzing these temperature changes. The second residual fragment from the bending test was drilled out with a hammer drill and filled with thermal paste before the sensor needle was inserted. To ensure accurate measurements, good thermal contact between the sensor and the sample was ensured. Then, the thermal conductivity of each mortar was tested in the climate chamber at a temperature of around 20 °C.

3 Characterization Results

Various tests were carried out both in the fresh and in the cured state of the cement mortars reinforced with textile fibers in order to evaluate the influence of the incorporation of two different types of fibers on the thermo-mechanical properties of the composite material. To ensure consistency and accuracy, three samples of the same composition were tested for each test and the mean was calculated and presented in the subsequent section.

3.1 Density Testing

The graph presented in Fig. 2 shows the changes in bulk density of cement mortar reinforced with the two types of fibers. With a value of 1900 kg/m^3, the plain mortar shows the highest density both in the fresh and in the dry state. However, the addition of Type I and Type II fibers in different proportions resulted in a drop in bulk density. With type I textile mortar, the fresh bulk density decreased to 1585 kg/m^3, while with type II textile mortar it dropped to 1710 kg/m^3. In addition, the dry bulk density of composites with 40% textile fibers was reduced by approximately 300 kg/m^3 and 150 kg/m^3 for Type I and Type II textiles, respectively, compared to the ordinary mortar. Notably, Type II textile-reinforced composites exhibit higher bulk density values than Type I textile-reinforced composites in both the fresh and dry states. These results suggest that the incorporation of textile fibers can potentially produce materials suitable for thermal insulation applications.

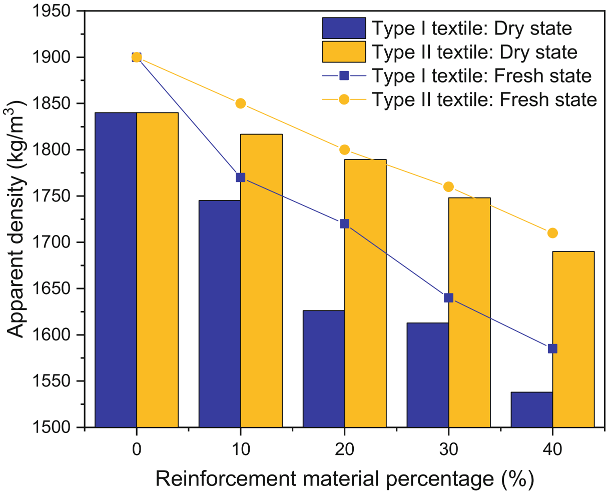

Fig. 2. Fresh and dry bulk densities of the textile fiber-reinforced mortars.

3.2 Mechanical Characterization

Figure 3 and Fig. 4 show the findings of the compressive and flexural strength tests performed on all mortar types after 7 and 28 days of water curing, respectively. It can be noticed that increasing the curing time resulted in an improvement in the mechanical performance of all cementitious mixes. For example, after 28 days, the plain mortar experienced a compressive strength increase of about 13% compared to 7 days of curing. Likewise, the flexural strength of the control sample increased by 34% between days 7 and 28, as shown in Fig. 4. Figure 3 illustrates the changes in the compressive strength of cement mortar after the integration of the two types of textiles. Notably, the Type II textile-reinforced samples exhibited higher compressive strength values compared to the Type I textile-reinforced samples, regardless of curing time. In contrast, the incorporation of Type I textile into the cementitious mortar led to a slight decrease in compressive strength. The addition of 40% of this textile resulted in a reduction in compressive strength of approximately 33% after 7 days of curing compared to plain mortar. However, when the same mix was cured for 28 days, it showed a decrease of about 9% compared to the 28-day control mortar. However, when Type II textile fibers were added to the cement mortar, there was a slight improvement in compressive strength values compared to ordinary mortar. In particular, the mix containing 40% Type II textile fibers showed a 16% increase in 7-day compressive strength and a 21% increase in 28-day compressive strength compared to the mixture with no fibers. In addition, the mechanical compression test results imply that both types of fibers exhibit superior mechanical performance compared to previously tested materials such as rice husk ash [28], expanded polystyrene [29], vegetable synthetic sponges [30], and crumb rubber [31].

Figure 4 shows the outcomes of the bending tests conducted on all the fiber reinforced-cement composites. Similar to the compressive strength results, the Type-II textile-reinforced mortars show higher mechanical performance than the Type-I textile-reinforced mortars after both 7 and 28 days of curing. However, increasing the amount

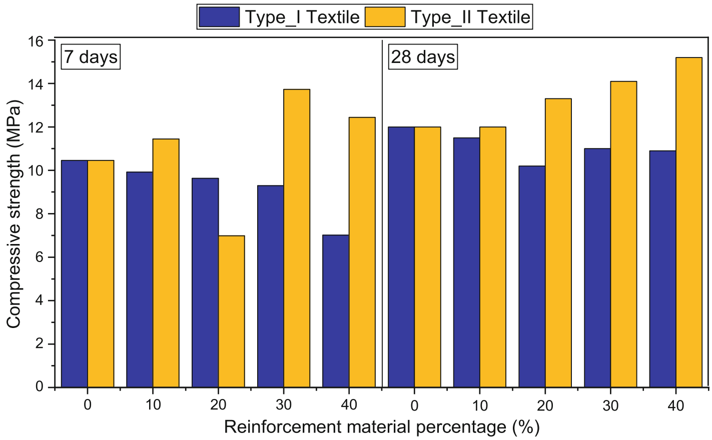

Fig. 3. Compressive strength of textile-reinforced mortars after 7 and 28 days of water curing.

of both fibers resulted in an increase in flexural strength regardless of the curing time. The samples with 40% Type-I textile and 40% Type-II textile showed approximately 34% and 55% increase in 7-day flexural strength, respectively, compared to the ordinary sample. In addition, the 28-day flexural strengths of the 40% Type-I textile sample and Type-II textile sample were increased by 22% and 36%, respectively, compared to the plain sample.

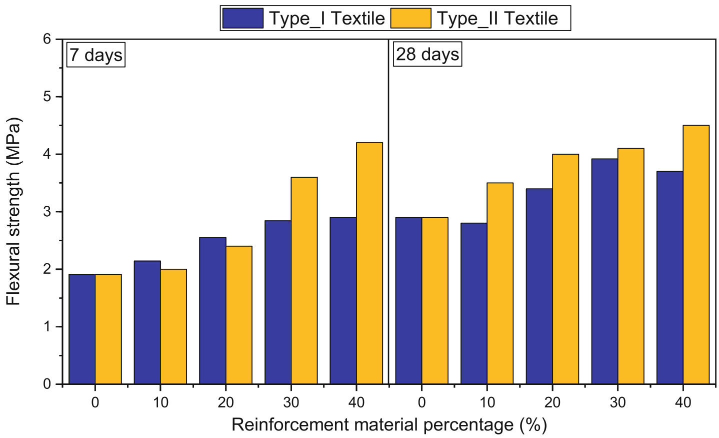

Fig. 4. Flexural strength of textile-reinforced mortars after 7 and 28 days of water curing.

3.3 Thermal Characterization

Figure 5 shows the change in thermal conductivity of all the textile-reinforced composites after being cured for 7 and 28 days. Regardless of the type of textile fibers used, an increase in the proportion of reinforcing material led to a decrease in thermal conductivity. Of all the mortars in the same category, those reinforced with 40% of each textile type had the lowest thermal conductivity. Comparing the plain mortar to the composite reinforced with 40% Type I textile, it can be noticed that the 7-day thermal conductivity decreases as more fibers are added, resulting in a difference of about 46%. In addition, the 10% Type II textile-reinforced mortar shows a greater reduction in 7-day thermal conductivity compared to the 10% Type I textile sample, which falls to a value of 1.08 W/m K. However, increasing the integration of Type II fibers from 10% to 40% only slightly reduced the thermal conductivity, with a difference of 16%. As for the 28-day thermal conductivity, both textile types showed similar results with values of 0.75 W/m K and 0.8 W/m K for the 40% Type I fiber mortar and the 40% Type II fiber mortar, respectively. This improvement in thermal conductivity due to the incorporation of textile fibers is consistent with previous studies showing that increasing the amount of fiber material improves thermal resistance [32]. Furthermore, the thermal performance of cement mortar was significantly enhanced by both Type-I and Type-II textile fibers, exceeding the performance of previously tested materials such as polymer-coated perlite [33]. These findings indicate the superior thermo-mechanical abilities of these fibers in reinforcing mortars, and imply that both types are well-suited for use in thermal insulation applications.

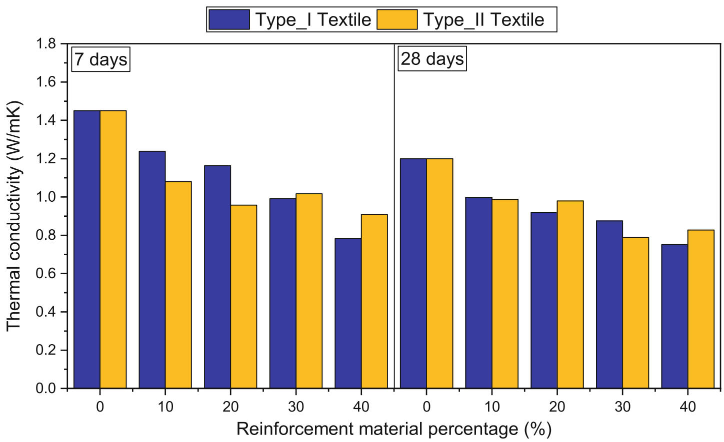

Fig. 5. Thermal conductivity of the textile-reinforced mortars.

4 Conclusions

Through experimental evaluation, this study investigated the effect of incorporating two distinct textile fibers into a cement-based mortar on its thermo-mechanical properties. The study found that:

– Both fiber types caused a decrease in bulk density, with Type II textile-reinforced composites exhibiting higher values than Type I composites in both fresh and dry states.

- Longer curing periods increased compressive and flexural strengths.
- Type II textile-reinforced mortars showed higher compressive strength than Type I samples after 7 and 28 days. Moreover, Type I fibers slightly decreased compressive strength and Type II fibers slightly increased it, compred with plain mortar.
- Increasing the percentage of both fiber types resulted in an increase in flexural strength. However, Type II textile-reinforced mortars showed greater flexural strength than Type I mortars after 7 and 28 days.
- Increasing the proportion of both types of fiber led to a decrease in the thermal conductivity of cement mortar.

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Nature-Based Solutions for Sustainable Urban System Transformation: Addressing Circularity in Building System Recovery

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Abstract. Urban system transformation in view of sustainability is fundamental for efficient adaptation and mitigation of challenges faced by cities. Sustainable urban transitions, under the umbrella of circular economy, are key to effectively addressing future challenging scenarios and their impacts. The adoption of nature-based solutions (NBS) for circular resource management can provide beneficial ecosystem services to the urban built environment while promoting the conservation and reuse of resources within the urban cycle. The Circular City framework outlined the use of NBS to tackle challenges related to urban circularity. One such challenge is 'Building system recovery', which involves the regeneration of the built environment. By implementing NBS, the lifespan of building systems, construction materials, buildings, as well as open spaces can be extended. This is achieved by reducing exposure to weathering from external agents, thereby reducing the rate of infrastructure renovations, retrofitting and replacements. Moreover, strategies that prioritize resource savings, greener environments, and water-sensitive systems can increase resilience by providing critical ecosystem functions such as stormwater management, greywater treatment and mitigation of the urban heat island effect. Building upon the Circular City framework, this contribution presents NBS units and interventions at different urban scales – materials, components, systems – aiming at addressing the circularity challenge of 'Building system recovery'. This is followed by a comprehensive analysis of input and output resource streams for strengthening circularity solutions in cities. This contribution describes state-of-the-art circularity frameworks aiming at supporting decision-makers and practitioners, while providing guidance tools for involving all relevant stakeholders, thereby supporting multifunctional implementation of NBS for inclusive and resilient circular cities.

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Keywords: Urban Built Environment · Green Infrastructure · Circular Economy · Circularity Challenges · Circular Buildings · Nature-Based Solutions

1 Introduction

1.1 Enhancing Urban Resilience by Circular Nature-Based Systems: The Circular City Framework

In recent decades, rapid urbanization and population growth have intensified environmental challenges, including climate change and ecosystem decline. The global goal is to shift towards sustainable, renewable products, and green technologies; being promoted initiatives to emphasize regenerative circular economies focusing on resource optimization, energy efficiency, and waste management. Nature-based solutions (NBS) involve integrating nature into urban environments, incorporating nature-inspired ideas into urban design. The relevance of NBS is closely tied to the concept of circular economy (CE), which advocates for restorative design solutions to minimize resource input, energy consumption, and emissions.

As an illustration of the synergies among the concepts of CE and NBS, the Circular City research framework seamlessly integrates the application of NBS in cities with the principles of CE [1–4]. This framework draws inspiration from the seven 'Urban Circularity Challenges' (UCCs, UCC_1–UCC_7) proposed by Atanasova *et al.* [5], which NBS can address effectively [6–10]. The UCCs that NBS can adopt within circular systems encompass: 'Restoring and maintaining the water cycle' (UCC_1); 'Water and waste treatment, recovery and reuse' (UCC_2) [8, 11–13]; 'Nutrient recovery and reuse' (UCC_3) [14, 15]; 'Material recovery and reuse' (UCC_4); 'Food and biomass production' (UCC_5) [7, 16]; 'Energy efficiency and recovery' (UCC_6); and, 'Building system recovery' (UCC_7) [1–5, 17, 18]. The framework englobes 39 NBS units (NBS_u), 12 interventions (NBS_i), and 10 supporting units (S_u), classified in nine sectoral categories: (1) 'Rainwater Management'; (2) 'Vertical Greening Systems and Green Roofs'; (3) 'Remediation, Treatment, and Recovery'; (4) '(River) Restoration'; (5) 'Soil and Water Bioengineering'; (6) '(Public) Green Space'; and, (7) 'Food and Biomass Production'. A detailed methodology on the inputs and outputs (I/O) resource streams from the NBS_u/i is provided within the framework [1, 2, 7, 8]. To enhance the accessibility and usability of the framework for interested stakeholder groups, a comprehensive graphic tool has been developed. The guidance tool facilitates the automatic quantification of NBS_u/i resource streams – encompassing both I/O, and includes a descriptive toolbox that offers useful knowledge and guidance for users [19, 20].

The Building System Recovery Challenge. The seventh UCC (UCC_7) addresses the pivotal theme of regenerating the built environment; embracing architecture and infrastructure tailored for living, working, manufacturing, and various other activities. Through effective shielding from UV (ultraviolet) radiation and pollutants, buildings and open spaces contribute to the prolonged lifespan of prevalent building materials, consequently diminishing the frequency of necessary renovations or infrastructure replacements. This proactive approach not only extends the longevity of structures but also yields resource conservation benefits [1, 4, 5].

2 Materials and Methods

2.1 Holistic Approach to the Urban Built Environment

The COST Action CA21103 "Implementation of Circular Economy in the Built Environment" (CircularB) constitutes an excellent platform for science communication and knowledge sharing among a variety of disciplines and sectors. In the present research study, contributed CircularB experts from the fields of Engineering, Architecture, Urban Planning, and Environmental Sciences. Thus, transnational research opportunities served as a valuable tool to enrich the UCC_7 perspectives on the potential of NBS implementation by addressing CE and sustainable design strategies in the urban built environment.

Selection and Implementation of Nature-Based Solutions to Address the Building System Recovery Challenge. This research stands from the selection of NBS_u/i and S_u which contributes to the 'Building system recovery' challenge [1]. Considering relevant NBS_u/i and S_u selected by Langergraber *et al.* [1], CircularB experts complemented the framework of NBS relevant for the UCC_7; and, proposed an approach on how this is related with the UCCs network. Additionally, a case study is analyzed and presented as an exemplary best practice addressing the UCCs; and specifically, the UCC_7 [1, 2, 4, 5].

Fórum da Maia Case Study Implementation. The green roof system at the Maia Forum, Maia, Portugal was executed as part of BaZe (Maia Net Zero Carbon City, Living Lab); a living laboratory dedicated to decarbonization. One of the primary project objectives was to showcase a building solution inspired by nature; illustrating in practical terms, the manifold environmental, financial, and social benefits.

Description of Demands, Services and Quantification of Resource Streams related to Building System Recovery. This approach would enrich the Circular City guidance tool, by proposing the integration of the UCC_7, and, consequently the UCC_4 on 'Material recovery and reuse' [19, 20]. This, it will also serve as a basis for the development of the common international framework from the COST Action CircularB on circularity indicators.

3 Results and Discussion

3.1 Nature-Based Solutions of Relevance to Address the Building System Recovery, and Proposal of New Units to the Circular City Framework

Identification of Nature-Based Solutions to Potentially Address the Building System Recovery. This study complements the selection of NBS_u/i and S_u proposed by the Circular City framework [1]. Thus, different levels of implementation were proposed (Table 1), as well as the inclusion of new NBS_u/i into the framework which potentially addresses the UCC_7.

Table 1. The urban circularity challenge (UCC) on 'Building System Recovery' (UCC_7) addressed by nature-based solutions (NBS) units (*NBS_u*), NBS interventions (*NBS_i*), and Supporting units (*S_u*) (based on and adapted from Langergraber *et al.* [1] and Canet-Martí *et al.* [7]).

(code number) *NBS_u*, *NBS_i*, *S_u*[†]	UCC_7	
Rainwater management		
(7) Bioretention cell — *NBS_tu*	●	A,D[‡]
(S1) Rainwater harvesting — *S_u*	○	A,B,C,E
(S2) Detention vaults and tanks — *S_u*	●	A,B,C
Vertical greening systems and green roofs		
(13) Ground-based green facade — *NBS_tu*	●	B,C,E
(14) Wall-based green facade — *NBS_tu*	●	B,C,E
(17) Extensive green roof — *NBS_tu*	●	A,C
(18) Intensive green roof — *NBS_tu*	●	C,E
(19) Semi-intensive green roof — *NBS_tu*	●	C,E
Remediation, treatment, and recovery		
(21) Treatment wetland — *NBS_tu*	○	A,C,D
(24) Bioremediation — *NBS_is*	○	B,C
(25) Phytoremediation — *NBS_is*	○	A,B,C
(S5) Disinfection (for water recovery) — *S_u*	●	A,B,C
(S7) Physical unit operations for solid/liquid separation — *S_u*	●	A,B
(S8) Membrane filtration — *S_u*	●	A,B,C,E
Soil and water bioengineering		
(33) Soil improvement and conservation — *NBS_is*	●	C,D,E
(34) Erosion control — *NBS_is*	○	D
(35) Soil reinforcement to improve root cohesion and anchorage — *NBS_is*	○	D,E
(Public) green space		
(38) Green belt — *NBS_su*	○	A,D
(39) Street trees — *NBS_su*	○	D
(40) Large urban park — *NBS_su*	○	D
(41) Pocket/garden park — *NBS_su*	○	D
(42) Urban meadows — *NBS_su*	○	D
(43) Green transition zones — *NBS_su*	○	D

(*continued*)

Table 1. (*continued*)

(code number) *NBS_u*, *NBS_i*, *S_u*†	UCC_7	
Food and biomass production		
(44) Aquaculture — *NBS_tu*	●	A,D
(45) Hydroponic and soilless technologies — *NBS_tu*	●	A,B,C,E
(46) Organoponic/Bioponic — *NBS_tu*	●	A,B,C,E
(47) Aquaponic farming — *NBS_tu*	●	A,B,C,E
(49) Productive garden — *NBS_su*	○	D,E
(50) Urban forest — *NBS_su*	●	D
(51) Urban farms and orchards — *NBS_su*	●	B,C,D,E

†*NBS_tu*: technological units; *NBS_su*: spatial units; *NBS_is*: interventions soil; *NBS_ir*: interventions river.
●: addressing the challenge; and, ○: design dependent potential contribution (according to Langergraber *et al.* [1]).
‡Level and typology of implementation – *i.e.*, meso (buildings and infrastructure), and macro (cities and urban regions) – based on Canet-Martí and Pineda-Martos *et al.* [7]: (A) as urban blue infrastructure; (B) as green infrastructure (GI) in buildings; (C) as GI on buildings; (D) as GI for parks and landscape (urban level); and, (E) as GI contributing to building integrated agriculture [4, 10].

Potential NBS_u/i addressing the UCC_7, their descriptions and synonyms, are suggested to the aim of enhance the Circular City framework – as they were not included originally. This would be the case of bio-solar green roofs (Fig. 1), that would be characterized within the 'Vertical Greening Systems and Green Roofs' category (Table 1) [1–3] as integrated solar renewable energy (photovoltaic, PV) systems in green roofs; thus, improving biodiversity and energy efficiency.

Associations Among Building System Recovery and Other Urban Circularity Challenges. Urban greening and water aspects, and specifically related with vegetation in cities, are among the essential elements for the successful implementation of NBS at the urban scale – *e.g.*, both as an input and output resource stream (UCC_5, biomass production) [1, 2, 4, 7]. Designing urban water integrated NBS_u/i, implying systems with diverse design and purposes, aimed at addressing the UCC_7, also implies the consideration of other challenges, such as the UCC_1, UCC_2 and UCC_3 by adopting critical water resource strategies – *e.g.*, the use of greywater flows for irrigation, and other purposes such as non-potable water; specially, in those drought sensitive areas (Fig. 1). Urban planning instruments, policies and strategies benefiting from inter- disciplinary and sectoral collaborative networks are essential to boost the implementation of NBS in cities; being addressing multiple UCCs, simultaneously (Fig. 1) [2, 4, 7].

Fig. 1. A schematic simplified representation of the Urban Circularity Challenges (UCCs) integrated at the urban built environment – Building scale exemplification of the seventh UCC, on ‘Building system recovery’, and its associated circularity challenges network.

Potential Integration of Building System Recovery Challenge on the Circular City Toolbox and Guidance Tool. The graphic tool developed within the Circular City Toolbox includes different UCCs levels, such us: ‘Water and Waste Treatment and Recovery’; ‘Restoring and Maintaining the Water Cycle’; ‘Food and Biomass Production’; ‘Nutrient Recovery and Reuse’; and, ‘Energy Efficiency and Recovery’ (Circular City website, guidance tool [19, 20]. This study proposes the inclusion of the UCC_7 – to be complemented by the UCC_4, as part of the tool levels (Fig. 2). Thus, new demands – such as ‘Alternative component source’, ‘Building reuse’, and ‘Regeneration’; and services – ‘Collection/separation’, ‘Improve building insulation’, and ‘Microclimate regulation’ were included (Fig. 2). The challenge of ‘Building system recovery’, understood under an integrative circular thinking design, can be addressed by NBS_u/i (Table 1) [1] working as interconnected individual units or interventions where the resources flow by closing a common urban circular system (Fig. 2) [1–3, 19, 20]. Thus, the process of urban planning would been enriched from sectoral perspective integration aimed at giving value to the multifunctionality of NBS systems.

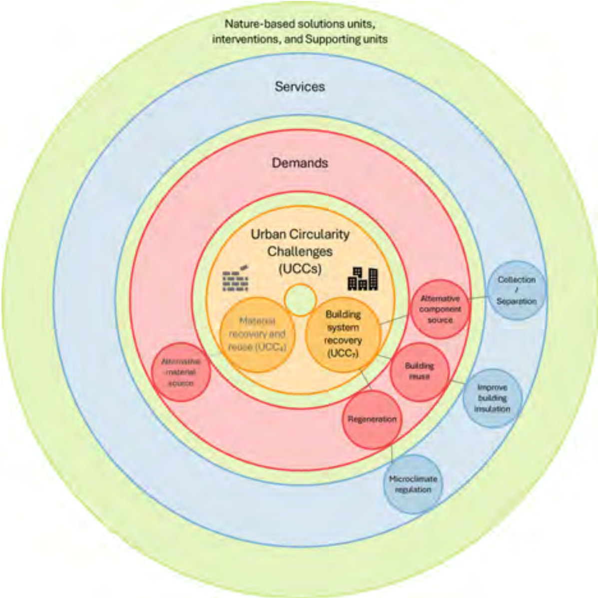

Fig. 2. Proposed role of 'Building system recovery' challenge in the Circular City toolbox ('Descriptive Toolbox') [3, 20] to promote the information model based on potential urban resource flows related to the seventh Urban Circularity Challenge.

3.2 Building System Recovery Best Practices: The Case of Fórum Maia

Design concept for the green roof at Maia Fórum (Fig. 3) was developed concurrently with spatial analysis; considering building characteristics, and the educational aspect intended from the project. Thus, a deliberate choice was made for a straightforward and naturalistic design focused on enhancing biodiversity, maximizing greenery (addressing UCC_5), and facilitating occasional visitor access in a non-disruptive manner. Design encompassed terrain modeling and vegetation composition, predominantly using native species – *e.g.*, *Verbena bonariensis*, *Thymus serpyllum*, and *Corynephorus canescens*; highly adapted to regional climate, and well known for their effectiveness in promoting biodiversity. Two main vegetation layers vary between lower-growing species, about 20 cm; and, intermediate species, about 1 m in height. Their diverse textures, growth patterns, and flowering cycles contribute to a visually pleasing composition that maintains sensory appeal throughout the year. This green roof is intended to function as a living laboratory, for which thermal and humidity sensors have been installed, along with an interconnected and monitored meteorological station (monitoring $UCCs_{1,2,6}$). The project comprises the use of an ecologically designed green roof system, entirely produced in Portugal, based on expanded cork agglomerates (black cork blocks) (accomplishing $UCCs_{4,7}$). Among the main ecosystem services it provides, the following are identified: (i) promotion of flora and fauna biodiversity within the urban built environment ($UCCs_{5,7}$); (ii) retention and reduction of the rainwater drainage rate, and promotion of sustainability of urban drainage systems ($UCCs_{1,2,3,7}$); (iii) comfort and thermal efficacy, providing better insulation and contributing to enhance the energy efficiency of the building ($UCCs_{6,7}$); and, (iv) mitigation of the urban heat island effect by absorbing and dissipating heat, thus reducing the overall temperature in urban areas ($UCCs_{6,7}$). This contributes to a more comfortable and balanced microclimate and helps combat the higher temperatures typically experienced in densely built urban areas.

Fig. 3. Semi-intensive green roof implemented at Fórum da Maia, Maia, Portugal.

4 Conclusions

Cities must transform for sustainable futures; thus, reinforcing their ability against existing urgent challenges, such us resource scarcity, climate change, and ecosystem degradation couple with biodiversity loss. Nature-based solutions (NBS) as multifunctional systems, offer valuable ecosystem services to the urban biosphere. Moreover, by adopting the concept of circular economy, NBS implementation supplements the support towards sustainable transformation of the urban built environment. NBS in urban regeneration effectively addresses the 'Building system recovery' challenge (UCC_7), with circular buildings positively impacting materials, energy, waste, health and well-being, and biodiversity ($UCCs_{1-6}$).

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Alternative Growing Medium for Indoor Living Walls to Foster the Removal Efficiency of Volatile Organic Compounds

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Abstract. Increasing urbanization trends led to growing concerns regarding human health risks linked to long-time exposure to poor indoor air quality. Volatile Organic Compounds (VOCs), *e.g.*, formaldehyde and benzene, are the most significant pollutants in indoor environments due to the high number of sources contributing to increase their concentration. Vertical Greening Systems (VGSs) have been proven as space-efficient nature-based solutions (NBS) using the ability of ornamental plants in removing VOCs. Growing media and rhizosphere community often play a pivotal role in removing indoor VOCs, especially in active biofilters. Although horticultural substrates are often overlooked in VGSs' applications, an increasing number of studies focus on: (i) investigating sustainable opportunities provided by organic materials to produce alternative growing media; and, (ii) exploring compositions of substrates to maximize VGSs phytoremediation efficiency. This work presents preliminary results on the influence of almond shells as an alternative growing medium for VGSs on the removal efficiency of formaldehyde. For that, a VGS module with almond shells as substrate and a single species of ornamental plant was placed in a sealed chamber – specially designed to recirculate the air contaminated by formaldehyde through the module acting as an active biofilter. The system produced a clear reduction of the formaldehyde concentration, and the plants developed correctly with the substrate. Green building-integrated systems are multifunctional NBS which address challenges such as human wellbeing and circularity at local scale. Using organic growing media to improve the biofiltration capability of these systems is a promising alternative towards successful implementation in the built environment.

Keywords: Nature-Based Solutions · Green Infrastructure · Vertical Greening Systems · Indoor Air Quality · Formaldehyde

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1 Introduction

In the framework of cities' densification, Vertical Greening Systems (VGSs) – well known as green walls or living walls (synonyms) – are adopted as technological nature-based solutions (NBS) to improve citizens' well-being through the naturalization of the built environment [1–3]. This term refers to a wide umbrella concept that describes varied technological NBS adopted for growing plants vertically, attached or not to a building facade or to an interior wall [2–6]. Many scientific studies assert that the adoption of VGS technology and solutions provide multiple benefits in outdoor applications, such as the improvement of air quality; the mitigation of the urban heat island (UHI) effect; the improvement of buildings' performance – by acting as thermal insulation and reducing the UHI effect; the support of biodiversity enhancement in cities; and, the management of stormwater [6–8]. However, the increasing urbanization trend led people to spend almost 80–90% of their daily time in indoor environments such as schools, homes, workplaces, and other interior public spaces [9]. Besides ambient pollution, urban areas present critical issues linked to the indoor air quality (IAQ); and there is a growing public awareness regarding risks linked to the long-time exposure to poor IAQ at home and workplaces in terms of health diseases [10]. Volatile Organic Compounds (VOCs), such as formaldehyde (CH_2O) and benzene (C_6H_6), are the most significant pollutants in indoor environments due to the relative high number of sources – *e.g.*, paints, furniture, and textiles – that contribute to increase their concentration in interiors if compared to outdoor air pollution.

Some scientific studies have investigated the ability of ornamental potted-plants species in removing VOCs from air [11, 12]. Even if potted-plants demonstrate significant removal efficiency of indoor air pollutants, on-site application highlights space-related limitations in order to obtain consistent effects in air cleaning process. Vertical Greening Systems have been tested as a space-efficient strategy to expose a greater plant biomass to indoor air pollutants. As an example, previous studies have tested the performance of felt-based living wall set-ups with different ornamental plant species, obtaining promising results concerning the reduction of total VOCs [13, 14]. In this framework, Godish and Guindon [15], and Wolverton *et al.* [16] demonstrated independently in the year 1989 that plant's cultivation substrate plays a pivotal role in removing VOCs from indoor air than plant's foliage responsible of gas exchanges. Later, outcomes obtained by Hörmann *et al.* in 2018 [17] revealed the important role of the rhizosphere during air biofiltration. These findings lead to focus on cultivation substrate composition, such as the activated carbon substrate [18], and treatment conditions that stimulate the growth of active microbiota able to degrade pollutants. This is particularly important for the application of active air biofilters that use pressure to increase the volume of air in contact with the vegetation and substrate cultivation to increase the phytoremediation efficiency of VOCs – if compared to passive living walls, as reported by Pettit *et al.* [12] and Irga *et al.* [19]. As there is an increasing interest on the ability of VGSs to reduce airborne contaminants, further studies are needed to better understand how environmental conditions and living wall characteristics may influence the potential of indoor vegetation for the IAQ improvement.

Growing media play a crucial role to obtain successful VGSs in terms of aesthetical values and efficiency of phytoremediation processes. Varied inorganic and organic growing media can be used depending by the kind of VGS to be implemented. Nowadays, increasing attention must be focused on investigating alternative substrates obtained by reusing waste and by-products derived from local industries and activities such as the agri-food sector related, in order to enhance these bio-resources under a circular economy (CE) perspective and increasing the sustainability of VGSs [20]. In this framework, the present study investigates the phytoremediation efficiency of a VGS module that adopts almond shells as a growing media for common indoor ornamental plants. Almond shells have been selected due to the large availability of this ligneous by-product in Andalusia (southern Spain) with potential features to be exploited towards circular bioeconomy strategies [21, 22]. This research study aims to enhance almond shells as a potential growing medium for VGS applications thanks to their properties [22] and to fill the knowledge gap on how the use of varied alternative growing media for indoor living walls may influence the formaldehyde removal ability of common ornamental plants. The research focuses on the knowledge improvement regarding phytoremediation processes of formaldehyde, as the most widespread VOC in interiors that cause severe health diseases if people are exposed for long periods. Moreover, the research conducted on alternative growing media is inspired by the principles of CE; moving towards an eco-design approach and by reducing the environmental impact of substrates used in VGSs [1–3, 6, 23, 24].

2 Materials and Methods

This study has been designed to compare the evolution trend of formaldehyde concentration in a glass sealed chamber with and without a VGS module. A Fytotextile system® of 1 m^2 – *i.e.*, 1 m length; 1 m height – and composed of 49 pockets has been adopted to set up the VGS module. *Chlorophytum comosum* (Thunb.) Jaques, commonly known as spider plant, has been selected due to its diffusion as ornamental and evergreen perennial indoor plant species. Moreover, *C. comosum* is often used in indoor VGS applications thanks to its ability to remove airborne contaminants from indoor air [16]. Eighteen plants of *C. comosum* were arranged in pockets of the Fytotextile module filled with almond shells as growing medium (Fig. 1). Almond shells were previously collected from a local company operating in the cultivation and processing of almonds (DAFISA S.A., La Carlota, Córdoba, southern Spain). Almond shells were cleaned with regular water to remove small particles and dust than can affect the performance of the VGS module inside the sealed chamber. The VGS module was placed in interiors for 4-weeks acclimatization and growth stabilization supplied with artificial lighting and irrigation.

Almond shells-growing medium was characterized determining its physical properties: (i) the particle size distribution; (ii) the dry bulk density ($g{\cdot}cm^{-3}$); (iii) the total porosity (%); and, (iv) the water holding capacity (%). The particle size distribution was performed by using a set of mesh sieves with opening dimensions between 0.5 mm and 16 mm. While the dry bulk density and the water holding capacity were determined through the procedure proposed by Maiti [25], and the total porosity following the method indicated by Landis [26].

Fig. 1. On the left, almond shells collected and cleaned before being used as growing media; and, on the right, a plant of *Chlorophytum comosum* set up in almond shells-growing medium contained in a pocket of Fytotextile VGS module.

Formaldehyde was released in a sealed glass chamber of 2 m^3 volume – *i.e.*, 2 m length; 1 m depth; 1 m height – equipped with artificial lighting, at an orientation angle of 14° to the horizontal, and a recirculating ventilation system used to circulate air thorough the VGS module with an air flow of 0.5 $m \cdot s^{-1}$. Formaldehyde concentration ($mg \cdot m^{-3}$) inside the sealed chamber was monitored using the YESAIR 8-Channel IAQ Monitor (Critical Environment Technologies Inc.); a portable air quality detector that was placed inside the sealed chamber during tests. The air quality detector is also equipped with a sensor to monitor temperature (ºC) and relative humidity (%). Initial volume of 1 ml formaldehyde was used to reach the maximum concentration inside the sealed chamber – close to the safe threshold limit of 0.37 $mg \cdot m^{-3}$, indicated by the Instituto Nacional de Seguridad y Salud en el Trabajo (INSST), Spain [27]. The formaldehyde was released through a pipette into the sealed chamber once at the beginning of each test, and the formaldehyde concentration trend was monitored in continuous for 60 min; being 1 min sampling.

The study has been performed to compared two scenarios of formaldehyde concentration trend: (1) in the empty sealed chamber (control test); and, (2) the sealed chamber equipped with the VGS module working as biofilter. In the second scenario, the VGS module was placed inside the sealed chamber and connected to the recirculating ventilation system in order to force the contaminated air to pass and recirculate through the vegetation. Tests have been performed in triplicates for both scenarios, and at a temperature range of 24.2–30.0 ºC.

3 Results and Discussion

3.1 Characterization of Almond Shells as Growing Medium for Vertical Greening Systems

Two of the main functions of growing media are to provide support for roots growth; and, retain and make water available. Physical properties of a substrate provide important indication to establish the suitability of alternative materials to be used as growing media for soilless cultivations. Table 1 shows initial physical properties of almond shells used as growing medium for ornamental plants. Almond shells have been used as collected by the local company without any pre-treatment process. They present a coarse particle size distribution consisting of 89.62% particles with a diameter equal or greater than 8 mm.

Table 1. Physical properties of almond shells used as growing medium in this study.

Distribution of particle size	
Diameter (mm):	Particle size distribution (% particles):
16	4.91
8	84.71
4	9.26
2.5	1.04
1	0.04
0.5	0.04
<0.5	0.01
Dry bulk density: 0.31 g·cm^3	
Total porosity: 68%	
Water holding capacity: 20%	

This result indicates that almond shells produce a porous and aerated substrate that presents an adequate initial dry bulk density of 0.31 g·cm^{-3}; according to Fernandes and Corá [28]. On the other hand, the total porosity and the water holding capacity presented values quite low, compared with those ranges recommended for an optimal substrate [29, 30]. Indeed, authors as Schafer and Lerner [29] and Evans [30] indicated that the total porosity of an ideal substrate should be between 75% and 90% [29, 30], while the water holding capacity is recommended to be between 50% and 65% [30]. Anyway, Tripepi [31] indicated that total porosity in the range of 50–85% is considered satisfactory; and, that the general range of water holding capacity is between 20% and 60% for many substrates used as potting mix. Considering the low water holding capacity of almond shells, the irrigation system of VGS module used in this study has been set to supply water during 15 min·h^{-1} for 24 h.

3.2 Comparison of Formaldehyde Concentration Trends

The comparison of formaldehyde concentration trend in the sealed chamber with and without the VGS module is shown in Fig. 2. In all cases, the initial formaldehyde concentration inside the sealed chamber was 0 mg·m^{-3}. Figure 2 shows both trends when formaldehyde concentration reached the maximum level. In tests with the empty sealed chamber, a single injection of formaldehyde in liquid state – *i.e.*, 1 ml volume – produced a maximum mean value of 0.53 mg·m^{-3} (see Fig. 2) that was consistently higher than in experiment that use vegetation as biofilter (0.35 mg·m^{-3}); being a difference of 0.18 mg·m^{-3}.

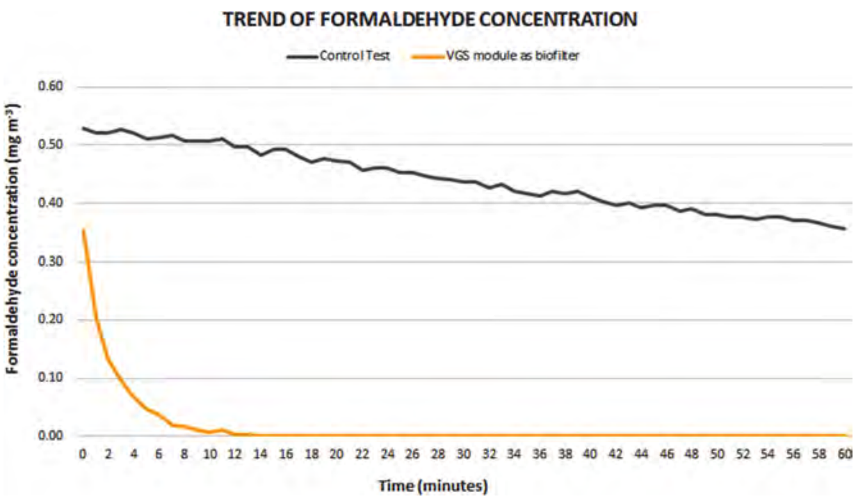

Fig. 2. Comparison of the concentration trend of formaldehyde (CH_2O) measured in the glass sealed chamber during the control test (dark grey line trend); and, the test performed using the vertical greening system (VGS) module acting as biofilter (orange line trend).

The formaldehyde concentration presented decreasing trends in both scenarios during 1 h of monitoring. In the test performed in the empty chamber the concentration of formaldehyde decreased by 0.17 mg·m^{-3} from the maximum value, reaching 0.36 mg·m^{-3} after 1 h of monitoring. While in tests with VGS module as botanical filter, the formaldehyde concentration decreases to 0 mg·m^{-3} from the maximum value, after 12 min of monitoring.

These results show the effectiveness of VGSs as botanical filter, and their contribution to the improvement of IAQ. The presence of vegetation inside the sealed chamber contributed to mitigate the concentration of formaldehyde. Indeed, formaldehyde reached a concentration value of 0.53 mg·m^{-3} – that is above the limit indicated by the INSST (0.37 mg·m^{-3}) [27]. On the other hand, the contaminated air inside the sealed chamber, that was in contact with plants and substrate of the VGS module, presented a maximum value of formaldehyde concentration, which was below the safe threshold limit of the INSST.

The control test presented a decreasing trend of 0.00–0.01 mg·m^{-3}·min^{-1} maintaining consistent the concentration of formaldehyde produced by a single inject during the whole experiment. On the other hand, the presence of the VGS module was fundamental to limit and reduce the formaldehyde concentration – *i.e.*: the maximum level registered was 0.35; and, after 1 min the concentration value was reduces to 0.20 mg·m^{-3} (−0.15 mg·m^{-3} from the maximum value) and after 5 min it is at 0.05 mg m^{-3} (−0.30 mg m^{-3} from the maximum value). This result demonstrates the efficiency of the removal ability of the VGS module at the beginning of the monitoring; after that, the formaldehyde concentration reached the maximum value.

4 Conclusions

The present research outcome highlights the importance of Vertical Greening Systems (VGSs) that use active airflow to improve the indoor air quality by efficiently removing formaldehyde, as one of the most significant volatile organic compounds. The results of this study are in line with those obtained in previous studies [13, 14]; and they suggest promising outcomes concerning the use of alternative materials for VGS substrates. This research contributes to the knowledge improvement about the role of VGSs as botanical biofilters [12, 19]; and, in particular, it demonstrates their effectiveness when exposed to low concentration of air contaminants. The physical characterization of almond shells as growing medium showed potential results for current and future studies in the research field. Further investigations are recommended to better understand the evolution trend of almond shells as alternative growing medium for VGSs, in terms of biological stability and chemical properties. This contribution demonstrates potentialities offered by VGSs as tool to ameliorate the quality of air inside buildings, especially in those equipped with mechanical ventilation systems. The present results obtained using almond shells also suggest exploring the opportunities of other by-products and waste materials to be used as alternative growing media, moving towards a circular economy perspective in vertical greening applications.

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Circular Economy in Construction: Harnessing Secondary Materials from End-of-Life Tires for Sustainable Building

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Abstract. The concept of the circular economy has rapidly gained traction as a transformative approach to sustainable resource management. Central to this paradigm is the emphasis on recycling and repurposing waste materials to ensure their maximum re-utility and minimal environmental side-impact. Over the myriad of waste materials, end-of-life (ELT) tires have emerged as a particularly significant resource, which has been underestimated in the past. However, the advent of advanced recycling technologies has illuminated the latent value embedded within these tires. From their rubber granules and steel components to fibrous materials and carbon black, each element holds potential for repurposing. Notably, the construction industry has been identified as a prime sector for the integration of these recycled materials, offering both durability and sustainability in building processes. Guided by the principles of the circular economy, this paper embarks on a comprehensive journey through the full lifecycle analysis of ELT tires. It delves into the intricacies of the recycling and utilization processes, shedding light on the myriad of potential value they present. Furthermore, a meticulous assessment and review are conducted on the contribution of these recycled tire by-products to the construction industry. The study revealed that recycling tires can result in a reduction in carbon emissions and provide substantial economic benefits. Specifically, for truck tires, the economic benefits can amount to 32.37 €, and the GHG emissions produced during the recycling process are minimal, only 1.13 kg of CO_2 equivalent for truck tires.

Keywords: Recycled Material · Tire Recycling · Waste Management · Construction Application · Sustainable Development · Circular Economy

1 Introduction

1.1 Background

Tires, owing to their versatility, durability, and relatively low cost, have found widespread applications, resulting in a gradual upswing in tire production in recent years [1]. According to statistical data, in 2019, global tire production reached an impressive three billion

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tonnes [2]. However, this substantial increase in tire production and consumption has led to a significant volume of discarded end-of-life (ELT) tires. Historically, the predominant methods for tire disposal were incineration and landfilling which increased the environmental concerns in world. In recent years, the concept of the circular economy has gained traction and is now being advocated by governments worldwide [3]. The key parameter, the circular economy integrates the principles of production, consumption, and waste management with the sustainable circulation of resources, aiming to keep an balance between economic growth and ecological sustainability [3].

Recycling and remanufacturing play important role in tire recycling based on the concept of circular economy, where three primary methods prevail: mechanical recycling, energy recovery, and fuel recovery. Mechanical recycling involves the disassembly of various tire components through mechanical means to extract valuable secondary materials. Energy recovery encompasses the incineration of tires in waste-to-energy facilities, harnessing their high calorific value to generate electricity. Fuel recovery entails the utilization of tires as supplementary combustion materials in cement kilns, contributing to cement production [4]. Mechanical recycling, in comparison to energy and fuel recovery, presents a more extensive scope for enhancement and versatility. This is due to the ease with which many secondary materials obtained from mechanical recycling can be processed and applied in various applications with minimal pre-treatment [4]. Nonetheless, owing to technological constraints, operational expenses, and the inherent variability in tire recycling processes, there have been limited instances in the commercial sector where tire recycling has effectively realized both of economic benefits and carbon emission reduction. This paper, guided by the principles of the circular economy, systematically summarizes the application of secondary materials during tire recycling within the domain of construction engineering.

2 Tire Recycling

Aiming to improve the efficient tire recycling and utilization commences with a comprehensive grasp of tire composition. In this regard, Table 1 provides a comprehensive breakdown of the constituent elements in the two predominant tire categories: passenger vehicles and truck tires. It becomes evident that truck tires exhibit distinctive characteristics, characterized by a higher proportion of natural rubber and a reduced content of carbon black as a reinforcement filler in comparison to passenger car tires [4]. This disparity can be attributed to the distinct performance demands imposed on passenger car tires, including low rolling resistance, improved skid resistance, and optimal wear properties [5]. From the preliminary analysis, it is noticeable that steel, rubber, and textile fibres stand out as the three most valuable and prevalent constituents within ELT tires.

Table 1. Materials component of passenger car and truck tires [4].

Composition	Passenger car tires	Truck tires
Natural rubber	22%	30%
Synthetic rubber	23%	15%
Carbon black	28%	20%
Other additives (e.g. curing agents, textiles)	14%	10%
Steel	13%	25%
Estimated average weight of new tire	8.5 kg	65 kg

2.1 Rubber Application in Construction

Due to their remarkable strength, flexibility, and strain control attributes, rubber granules are commonly utilized in concrete as a replacement for both fine(≤4.75 mm) and coarse aggregates(≤20 mm) [6]. For untreated rubber that has not undergone any solvent treatment, it is observable that its addition to concrete can enhance its flowability. According to Safan, Eid and Awad [7]'s findings, the addition of 15% rubber granules can increase the slump from 50 mm to 75 mm. Nonetheless, it can be affirmed that the inclusion of rubber effectively improves the workability of concrete. When maintaining the same water cement ratio value, Mohammadi, Khabbaz and Vessalas [8] found that adding 20% rubber granules could increase the slump from 15 mm, as noted by Tudin and Rizalman [9]'s discovery of a 21 mm increase with the substitution of 20% rubber granules. Due to the poor bond between the cement matrix and rubber, many researchers choose to treat rubber particles with 10 wt% NaOH before incorporating them into concrete which helps improve the interaction between concrete and rubber particles [8]. In summary, the introduction of rubber particles can contribute to enhancing the workability of concrete; however, the resulting impact is not substantial, leading to only a limited increase in slump. Moreover, it is noteworthy that the use of NaOH-modified rubber particles does not necessarily result in a significantly greater improvement in workability.

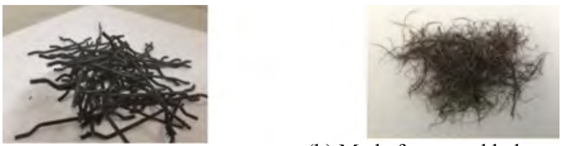
After a brief review, the addition of rubber leads to a substantial reduction in both compressive and flexural strength [8, 10–12]. However, when get comparison, the decrease in flexural strength is comparatively more modest. A examination in Ref. [8] for 7 days and 28 days reveals that rubber particles notably hinder the early hydration reaction. In contrast to the control group, which consists of plain concrete, rubber concrete exhibits a more pronounced increase in strength from 7 days to 28 days. In response to the challenge of reduced mechanical properties, several researchers have endeavoured to modify rubber to enhance the overall performance of rubber concrete. It is evident that NaOH-treated rubber concrete showcases superior mechanical properties in comparison to untreated rubber concrete [13]. While the addition of rubber has negative impacts on the mechanical properties of concrete, its contribution to other properties of concrete, particularly its durability should not be ignored. When rubber content is increased by 10–30%, the wear depth of the concrete can be reduced from 73% to 61% [14]. Furthermore, when maintain some rubber content, concrete with smaller rubber particle sizes show a lower wear depth. This is primarily due to the increased density of the concrete with the addition of rubber particles, resulting in improved abrasion resistance, as denser matrices generally exhibit better wear resistance [15]. In Ref. [14], compared to loose gravel particles, a compact and dense rubber concrete matrix is consistently advantageous in reducing carbonation depth. This is mainly because the addition of rubber generates fewer voids compared to ordinary concrete, thereby reducing carbonation depth. The same explanation can be applied to why rubber concrete exhibits better resistance to chloride ion penetration.

2.2 Recycled Steel Fiber Application in Construction

Among the materials employed to enhance the overall performance of concrete, steel fibres have gained significant popularity owing to their exceptional strength, effective crack control, high fracture toughness, and cost-effectiveness. Concurrently, as environmental consciousness continues to ascend, a group of scientists is delving into the utilization of recycled steel from scrap materials, following uncomplicated processing, to produce recycled steel fibre (RSF) as an alternative to industrial steel fibres (ISF). According to Fig. 1, it can be observed that the steel components of a tire primarily consist of two parts: tire steel wires and tire cord fabric. By using a wire drawing machine, we can obtain relatively intact tire steel wires (as shown in Fig. 2a). However, tire cord fabric is usually shredded along with rubber particles and then separated using a magnet, resulting in more irregular steel fibres (as shown in Fig. 2b). Compared to steel cord fabric fibres, RSF made from tire steel wires have more stable mechanical properties.

After a brief review, it has been observed that the inclusion of RSF and ISF have resulted in the decline of the slump flow. However, the RSF shows a less slump reduction than ISF in [16–18]. In Ref. [19], the author increases the dosage of superplastic to keep the same slump between ISF, RSF and plain concrete, which is 1.4 kg/m^3 for plain concrete, 1.19 kg/m^3 for concrete with RSF and 2.07 kg/m^3 for concrete with ISF. In Ref. [18], the author highlights the balling effect of RSF will cause an unusual increase the slump. The experimental results reveal that, the RSF have better performance than ISF on improving the compressive strength with show similar flexural strength improvement. A maximum compressive strength gain of approximately 64% was observed after the inclusion of about 0.3% RSF into the concrete[20]. The main reason behind this situation is assumed to be the addition of fibre lend to the decreased of capillary porosity, and low capillary porosity suppresses the development of micro-cracks. Compared to its excellent mechanical properties, similarly RSF reinforced concrete also exhibits remarkable durability. According to scanning electron microscopy (SEM) results, due to the high-strength extraction during mechanical recycling and the high-speed rotation during tire use, some carbon black and rubber particles are introduced into the tire steel wires and steel cord wires. These particles can densely envelop the surface of the RSF. For cost considerations, these rubber and carbon black particles are not deliberately removed during the production of RSF. The presence of these rubber and carbon black particles imparts certain characteristics of rubberized concrete to RSF reinforced concrete. For instance, it exhibits stronger resistance to permeability and corrosion, especially in terms of corrosion resistance, where it outperforms ISF reinforced concrete. Liew and Akbar [21] further elucidation, based on electrochemical results, indicates that RSF concrete have a corrosion probability of 90% in a 3.5% wt NaCl solution, and it was found that RSF are more susceptible to corrosion than ISF concrete. It cannot be denied that RSF exhibit relatively lower fatigue resistance. Being recycled materials and having undergone high-stress usage in tires, they endure more fatigue stress compared to ISF. However, in comparison to regular concrete, RSF reinforced concrete still offers superior fatigue resistance. Building upon Graeff, Pilakoutas, Neocleous and Peres [22]'s explanation, the optimal fatigue resistance is provided when the RSF content is at 2%.

Fig. 1. Tire structure and engineered layers [23].



(a) Made from steel wires (b) Made from steel belts and cord

Fig. 2. Different kinds of recycled steel fibre.

2.3 Recycled Textile Application in Construction

Compared to the extensive utilization of steel and rubber particles, the application scope of recycled textile fibres is notably more constrained. Nevertheless, textile fibres still find relevance in the construction and road construction sectors, contributing to the creation of sustainable thermal and acoustic insulation materials as well as fibre reinforced concrete. The extraction of textile fibres from ELT tires typically follows the process of rubber cutting and particle sieving, facilitated by a blower.

When adding textile fibres to concrete which can enhance the resistance to both bending and compressive stresses. Due to their low intrinsic weight, the impact of textile fibres on the overall weight of concrete can be neglected. Experimental results have shown that small dosages of recycled carpet polypropylene fibres ranging from 0.07% to 2% can significantly improve compressive strength, bending toughness, and flexural strength [24]. Similarly, the inclusion of recycled nylon fibres in cement mortar can increase the tensile strength of the composite material by 35% and improve toughness by 13 times [25]. Comparatively, the application of recycled textile fibres as thermal or acoustic insulation materials is more prevalent than their use in concrete. The sustainable application of recycled textile fibres, particularly the combination of wool and polyethylene fibre waste, can be effectively harnessed for thermal reinforcement within double-wall constructions. From the perspectives of wall temperature and heat flux, thermal insulation materials crafted from acrylic fibre waste can serve as competitive products. Moreover, their thermal conductivity and breathability closely resemble those of conventional building insulators, presenting a sustainable alternative [24].

3 Comprehensive Tire Recycling Process and Benefit Assessment

After a comprehensive comparison and discussion in the preceding sections, it becomes clear that secondary materials obtained from tire recycling hold significant potential for diverse applications within the construction industry. The primary objectives of this study are to delineate the essential mechanical and procedural steps for tire recycling and offer an initial assessment of its economic and environmental advantages for the construction sector.

3.1 Pre-treatment of End-Of-Life Tires

Two essential machines are necessary to do the pre-treatment of the ELT tire: the Wire Drawing Machine and the Rubber Shredder Machine. The Wire Drawing Machine assumes a pivotal role in tire recycling, primarily dedicated to the extraction of steel wires from ELT tires. The second critical machine of the ELT tire pre-treatment process is the Rubber Shredder Machine. The primary function of the rubber shredder is to classify the constituent elements of the tire for segregated processing which aims to ensures the effective separation of fibre products and rubber components within the tire. After the initial cutting of the materials, the subsequent step involves the separation of secondary materials. In this phase, a fibre classifier can be employed to remove the majority of the fibre materials, followed by the utilization of a magnetic separator to segregate the rubber and steel fibres. During this stage, the textile fibres can be directly incorporated into construction, while the steel cord fibres require additional screening to select the appropriate fibre gradation.

3.2 Sustainability Evaluation of End-Of-Life Tires

Based on the previous reviews of ELT tire recycling methods, the data can be compiled into Table 2, offering a concise presentation of the Greenhouse Gas (GHG) emissions associated and cost with each machine. This summary offers a more transparent environmental impact assessment of each recycling approach, facilitating more sustainable decision-making in the management of ELT tires within the context of a circular economy.

While the economic benefits of tire recycling may not be readily apparent – for instance, the value of utilizing recycled rubber in playground construction is not intuitively quantifiable – it is crucial to accentuate its importance in the circular economy. This study paid attention to the recycling of recycled rubber and steel fibres to assess their economic worth. Given the relatively low recycling rate of fibres, the economic value of steel wire and rubber proves to be more substantial, as outlined in Table 2. When did the cost benefit analysis, the pre-treatment machine only considered the electricity consumption, which price is calculated based on data from Ref. [32, 33]. For the

Table 2. Greenhouse gas emission and cost benefits for each recycling steps.

	GHG emission/CO_2 kg eq	Cost benefit/€
Pre-treatment for Tire/ton		
Tire wire drawing machine [26]	11.84	−5.27
Tire shredder machine [27]	7.20	−3.47
Fibre classifier [28]	0.45	−0.13
Magnetic separator [29]	0.05	−0.01
Steel recycling/ton		
Recycled steel fibre	-	1000
Rubber recycling/ton		
Rubber	-	327–568 [30]
Textile recycling/ton		
Textile fabrics	-	500–600 [31]

RSF, which match the half market prices of ISF (2 €/kg [34]). This method offered a realistic estimate of the economic value intrinsic to the recycling of these materials. These assessments underscore the significant economic potential of recycling materials, reinforcing the viability of tire recycling in a circular economy. GHGs where calculated using emission factors and activity data. Emissions where mostly calculated using Eq. (1).

$$GHG\ emissions = A \times E \quad (1)$$

where A = activity data (kWh/kg)

E = emission factor (kg CO_2e per kg/kWh).

GHG Emissions = kg CO_2e.

Upon comprehensive analysis and evaluation of each criterion, the overall recycling potential of ELT tires can be determined, as depicted in Table 3. Recycled rubber particles, recyclable steel fibres, and recycled textile fibres are the primary secondary materials in the recycling of ELT tires. Through economic and benefit assessments, it becomes evident that recycling a passenger car tire can generate 2.85 € in value, while recycling a truck tire can create 32.37 € in values.

Table 3. Greenhouse gas emissions and cost benefit for different type of tires.

Composition	Passenger car tire	Truck tire
GHG emission CO_2/kg eq	−0.15	−1.13
Cost benefit/€	2.85	32.37

4 Conclusion

The prevailing concept of the circular economy is more relevant than ever, and this article revolves around its principles. It delves into how, guided by these principles, ELT tires can be transformed into valuable resources, serving as an asset to the construction industry. Rubber particles, steel, and textile fibers are the primary secondary materials in the recycling of ELT tires. Although the addition of rubber particles to concrete may lead to a slight reduction in its mechanical properties, it offers high wear and corrosion resistance, rendering it suitable for various road construction applications. Moreover, its lightweight characteristics make it a viable choice for certain high-rise buildings, soundproofing walls, and fire-resistant materials. RSF have demonstrated significant potential to replace ISF, enhancing building characteristics not only in terms of cost but also environmentally. The substantial amount of useful textile fibers from tires can also be repurposed as fire-resistant or soundproofing materials.

A preliminary economic assessment indicates that the economic benefits can reach 32.37 € for truck tires, and the GHG emissions generated during the recycling process are limited, amounting to just 1.13 kg of CO_2 equivalent for truck tires. This study represents a novel attempt at comprehensive tire recycling, and it has the potential to assist in designing improved waste management strategies that simultaneously achieve economic benefits and environmental conservation. However, it is essential to acknowledge that this study represents only a preliminary analysis of the value of tire recycling. The data utilized is sourced from published articles and data repositories, and while the results provide valuable insights, the market applicability of these findings necessitates more specific and comprehensive data support. Further analysis and additional data are required to enhance the robustness of our conclusions and to more accurately reflect the true market value of tire recycling. We recognize the importance of ongoing research and data refinement in this field to contribute to a more comprehensive understanding of the value dynamics within tire recycling.

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Regenerative Approach in Sustainable Composite Structure Design for Building

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Abstract. By integrating living organisms and their intelligent capabilities at the heart of the design process, design evolves towards a creation in harmony with the surrounding nature. Therefore, the designer is led to reconsider the way they design sustainable solutions, capable not only of integrating but also of acting as living entities within their ecosystem. This approach promotes continuous interaction with the environment, fostering mutual enrichment where design and nature mutually enhance each other. Designers have the ability to reintegrate nature into the creation of materials and collaborate with natural resources. This reintegration fosters mutual positive impacts between natural and human systems. Such interactions lead designers to envision proactive scenarios for future habitats, merging scientific knowledge to co-evolve with nature. The design thus becomes a catalyst for transforming the design paradigm towards interconnectedness harmonious with the environment. In this context, it involves co-creation with living organisms from a perspective of bio-integrity rather than anthropocentrism, contributing to the regeneration of natural systems, restoration of human health, and preservation of biodiversity. While this approach presents a forward-thinking perspective, our empirical study seeks to demonstrate its potential implications in our daily lives and the real world. We have attempted to explore various methods and tests to incorporate the microorganism Ulva algae into the process of developing a living construction material, with the aim of promoting a locally regenerative approach.

Keywords: Living Design Regenerative Approach Research-Creation · Co-Creation · Sustainable Building Materials

1 Introduction

Currently, design is more than ever at the heart of the biological era where life emerges as a productive alternative. By integrating living organisms and their intelligent capabilities into the core of the design process, design has sought to surpass nature and envision “new life”, exploring novel symbioses between living beings and their environment, and consequently between the design object and its surrounding milieu. This is presented in the form of a “Living design” approach. This approach aims to transform the design paradigm towards a harmonious interconnection with the environment. Such interactions lead designers to consider proactive scenarios for future habitats, merging

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scientific knowledge to co-evolve with nature. This raises the question: how can design act as a catalytic agent to promote the sustainability and regeneration of healthy natural ecosystems?

Based on a research-creation approach, we have endeavored to present our empirical study that combines scientific knowledge with design perspectives to work with living organisms for a regenerative and sustainable approach. We were particularly interested in the specificity of the "ulva" algae, abundant in our locality, and its significant impact on the health of local biodiversity due to overproduction. Through various tests and experiments, we sought to explore the possibilities of incorporating these algae into the design of a "living" biomaterial to promote a regenerative approach. Our experimental study focuses on how to work with and mimic living organisms, aiming to regenerate natural systems rather than exploit and destroy them.

2 Living Design Contribute to Creating a More Sustainable Future

2.1 Synergy of Design and Synthetic Biology: Create «Alive»

Designers have embraced advancements in biology and technology, exploring innovative approaches to living organisms and their processes. By integrating the living and its vital intelligences into design, we have pushed beyond the traditional boundaries of design, not only drawing inspiration from nature but also working directly with the living itself to shape our future and "cultivate" life The biological revolution has given rise to a new generation of biologist-designers who are attempting to adopt a new line of research that guides their work in scientific reflection, enriching their ability to think within the full complexity of biology, whose principal actor is the living organism. Thierry Marcou, in his article "Towards a Design of Synthetic Life", introduces the concept of living design, where biology becomes a crucial tool in the designer's toolkit [1]. This synergy between design and biology has given rise to "scientific design", which "embraces scientific knowledge and works with new materials [2]. Scientific design involves a scientific approach based on research-creation. It represents a shift from object design to scientific creation, from agency to laboratory [2]. The objective extends beyond direct engagement with living organisms, it aspires to position a novel form of life at the core of design, fostering a new symbiosis with the surrounding environment and nature. These approaches involve treating the living as models, collaborators, and hackable systems for redesign, envisioning new life forms crafted by designers [3]. The designer-biologist, leveraging an interdisciplinary approach, possesses the capacity to create Hybrid Nature, Synthetic Nature, and Natural Nature. This growing synergy plays a pivotal role in the ecological transition towards "naturalizing" design [4]. The naturalization process aims to design new life forms by probing emerging systems of relationships around living entities, embodying the essence of this approach and establishing profound connections between the design object and its environment.

2.2 Inventing «Material Ecology»: Creating in Harmony with Natural Systems

The scientific designer aspires to explore a system of relationships that guides "living" matter to generate a material intricately interwoven with its environment. This perspective fortifies and reimagines the connection between design and nature, fostering the evolution of alternative, living, and intelligent materials. This interaction seeks to facilitate the seamless integration of these materials into the environment through the emergence of a new vital synergy, termed by Neri Oxman as Material Ecology [5]. Oxman defines it as a design philosophy, a research domain, and a scientific approach that delves into, elucidates, and expresses the relationships between the building, its environment, and its enhancement [6]. The underlying objective is to cultivate deeper connections between the design object and its environment while promoting an interrelation between buildings and the natural environment.

2.3 Living Design at the Center of a Regenerative and Sustainable Approach

Indeed, by integrating the living organism at the center of design processes, bio-design is moving more and more to create symbiosis with the nature. In this context, the biologist designer Carole Collet has defined living design as an approach to design based on a living system that integrates the learning from natural sciences and humanity in the service of regenerating biodiversity, climate, and communities [7]. Designers explore new strategies and aim to co-create with nature, actively participating in the preservation of local biodiversity while positioning humans as biological entities. This moves our frame of discourse from doing things TO nature' to one of participation as partners WITH and AS nature, promoting a regenerative approach [8]. Living design encourages a multi-species approach contributing to the regeneration of natural, social, and economic systems. It plays a key role in the ecological transition by creating strategies and materials that value nature rather than exploit it. Through the illustration (Fig. 1), we aimed to demonstrate how living design can offer new perspectives and solutions for a more sustainable future, in harmony with nature.

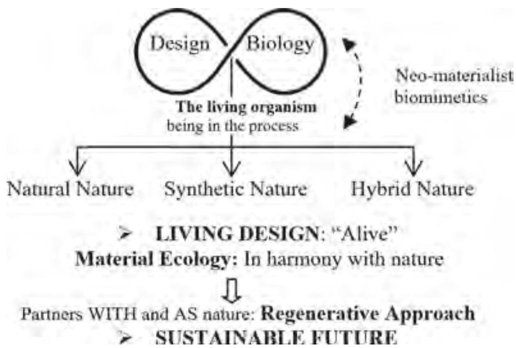

Fig. 1. Synthetic diagram: Living Design for a Regenerative and Sustainable Approach (made by the author).

3 When Eutrophication Inspires Bio-Design: Towards a Regenerative Approach in Tunis: Sfax

The exploitation of marine microorganisms, particularly algae, as a raw material is not a recent development. It has been utilized in various fields such as agriculture, food, cosmetology, and the creation of innovative design objects. Many bio-designers have now integrated algae as a central and fundamental element of their creations, using this resource as an architectural medium and building material. Aiming to valorize nature rather than consume it, in this experiment, we focused on co-fabrication with Ulva algae, classified as green macroalgae, which can become a marine hazard due to their proliferations but have the potential to be exploited as an organic resource in design conception (see Fig. 2).

Fig. 2. Eutrophication: Proliferation of green algae on the surface of the sea at Sidi Mansour, May 10, 2023. (taken by the author)

Building on an interdisciplinary approach, our reflection aims not only to develop a biomaterial but also to create a proactive scenario for future habitats, fostering continuous interaction with the environment. Our objective is to encourage a multi-species approach with a salutogenic intention.

3.1 Idea Projection

While green algae do not exhibit intrinsic toxicity and are even edible, their environmental impact is indirect and associated with their growth rate [9]. Given their abundance in our natural ecosystem, we aimed to transform this naturally occurring phenomenon that can be harmful to the local environment into a resource for creating sustainable construction materials.

We attempted to convey our reflections and the proposed regenerative perspectives through the following diagram (see Fig. 3). We have developed a construction material using local algae and silica-rich sand, with the goal of creating a material that has positive systemic impacts on natural, economic, and social aspects.

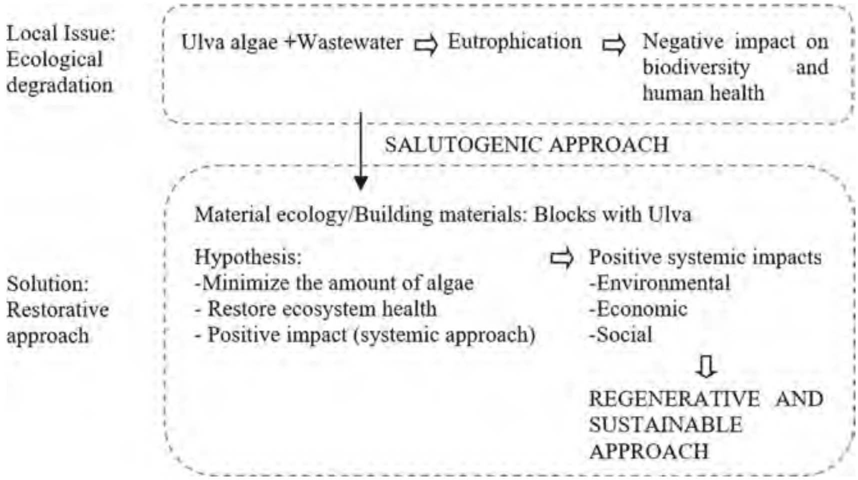

Fig. 3. Mental Map (made by the author)

3.2 Preparation and Experimental Testing

In our pursuit to determine how these algae could be applied in creating a lively and regenerative material, we conducted a variety of tests and experiments.

Step 1: Examining the optimal condition for integrating ulva algae into construction material design. This step involved conducting experiments with various forms of algae to assess their response to a new environment. Our observations suggest that the dry powder form of Ulva algae is more suitable for material design, exhibiting reduced vulnerability to degradation and mold formation compared to other forms.

Step 2: Exploring the optimal percentage of ulva powder to add to sand.

To determine the optimal composition of the mixture and the ideal concentration of Ulva algae in relation to silica sand, compression tests were conducted on specimens with varying algae concentrations (see Table 1).

Table 1. The different percentages of test specimens for the compression test. (Percentages are based on volume, not mass).

Designation	Sand (%)	Ulva Algae (%)	Density
T0	100	0	1.38
T1	50	50	1,3
T2	30	70	1,214
T3	10	90	1.14

The specimens measured 70 mm in diameter and 140 mm in height [10] (refer to Fig. 4).

Fig. 4. Specimens with a diameter of 70 mm and a height of 140 mm, featuring various percentages of Ulva for the compression test (taken by the author).

The purpose of this test was to generate stress/strain curves to assess the influence of adding algae powder, with the T0 specimen (containing 100% sand and 0% algae) serving as a reference (see Fig. 5).

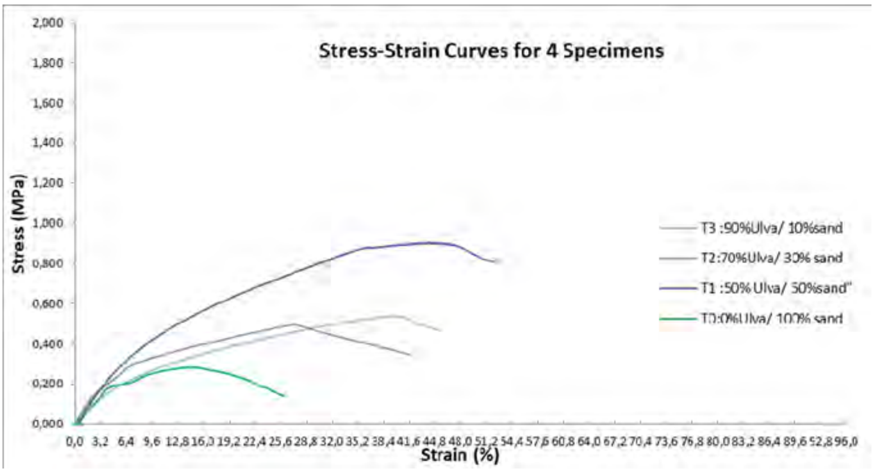

Fig. 5. Stress-strain curves of various specimens with different percentages of Ulva algae.

Upon analyzing these curves, depicted in Fig. 5, it was evident that the linear region was more pronounced for the T1 specimen containing 50% Ulva algae, displaying an elastic limit of 0.2 MPa. This indicates that the T1 sample had a higher capacity to withstand applied loads, demonstrating enhanced elasticity with an elastic modulus of approximately 3 MPa. However, the T2 and T3 specimens, with concentrations of 70% and 90% Ulva algae, resulted in a decrease in both maximum strength and elastic modulus compared to other specimens. These findings highlight that the 50% concentration significantly influences strength properties compared to our T0 reference, and the excessive increase of Ulva algae in the T3 specimen adversely affects the mechanical properties of the sample. In this context, the optimal formulation for our mixture involves considering Ulva algae powder as a reinforcing binder that enhances the stiffness of the specimen.

Step 3: Evaluating the impact of end-of-life ulva blocks on the natural ecosystem and local biodiversity.

To accomplish this, we conducted experiments with two aquarium fish, providing 2g of our material every other day. The fish flourished for over a month and a half, displaying sustained activity (see Fig. 6). This emphasizes the material's ability to supply nutrients (due to its high protein and mineral content) and establish a favorable environment for marine life.

The experiment commenced on June 5, 2023. The fish, which were fed our mixture died on July 30, 2023.

Fig. 6. Health and well-being of aquarium fish fed ulva-based material (taken by the author).

4 Advancing Toward a Circular Economy

These results reveal promising prospects for the potential implementation of our methodology in human creation. Bearing this in mind, a close collaboration has been initiated with the local company "SOIB" for the design of compacted blocks incorporating Ulva. These blocks are intended for use in the sustainable construction sector as part of a regenerative approach. Derived from the composition of SOIB's blocks and following numerous experiments, we created a block with the composition outlined in Table 2.

As depicted in Fig. 7, our blocks are manufactured using the specific mold from the company SOIB, with dimensions of 22 cm width, 23 cm length, and 11.5 cm height. This morphology ensures precise interlocking of the blocks [11].

Our emphasis is on creating positive impacts on both natural and socio-economic systems, fostering a circular economy. Our approach strives to improve the entire socio-ecosystem by encouraging the generation of local employment, revitalizing local communities, and regenerating life-support systems and their underlying resources, rather than depleting or altering them (Fig. 8).

Table 2. The Composition of Ulva Seaweed Blocks Manufactured by the SOIB Company

Percentages (%)	Quantity (kg)
50% Silica sand	6
25% Ulva powder	3
15% "Tbourba" land	1.8
8% "Tamra" land	0.96
2% cement	0.24
	Total: -/ + 12 kg

Fig. 7. Example of our Ulva building blocks (taken by author).

Fig. 8. Production of blocks using Ulva at a local company 'SOIB'.

5 Conclusion

Through direct engagement with living organisms, our experimental approach is designed to co-create with nature, emphasizing the valorization of natural resources over their exploitation. Our methodology prioritizes a multi-species approach, focusing on bio-integrity rather than anthropocentrism. Positioned between cultivation and fabrication, our framework is rooted in genuine material ecology, reintegrating our buildings and their components into their environment. It envisions a future where life seamlessly integrates with the built environment, and the built environment enhances life. We also aim to showcase the feasibility of utilizing living organisms, specifically Ulva algae, in the creation of alternative construction materials while highlighting challenges related to its physicochemical properties. This leads us to explore intrasectoral approaches to develop holistic solutions aimed at enhancing its insulation, strength, and rigidity. Although the materialization of nature-aligned construction blocks is still in the conceptual phase in terms of materiality, its functional process suggests a future where nature can reclaim its place, thanks to the potential of Living Design.

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Circular Value Chains and Stakeholders Engagement

Stakeholder Mapping for Value Creation of New Circular Business Models

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Abstract. In Circular Economy Management, various stakeholders play different roles that contribute to the value chain within the circular economy. These stakeholders need to be tracked and motivated to contribute to a circular economy. In addition, real estate developers as well as facility managers have a growing interest in both, the expansion of the value chain within the building as well as associated with facility services within the optimized building operation. The research approach is drawing upon real estate development projects as case studies. It maps the different stakeholders and analyses their role in the value creation. A range of new value creation stakeholders were identified and analysed to which extend their role is defined in traditional business models. The key benefits for owners and real estate investors comes from the adaptability to changing market demands, re-use and repurpose, low impact on urban ecology and biodiversity, innovative new real estate products among others. This study shows the benefits of encouraging stakeholders to actively participate in the co-creation and co-innovation of circular solutions. This involves identifying different stakeholders in the design and development of strategies, policies, and projects related to the circular economy. By defining their new role, diverse business models, as well as innovative and effective solutions can be developed.

Keywords: value creation · circular economy · business model

1 Introduction

1.1 Circular Economy in Real Estate and Facility Management

The traditional linear economic model, characterized by "take, make, and dispose" approach, has been a key driver of industrial nations' wealth. However, its significant limitations have recently become evident. In response, the Circular Economy (CE) emerges as a sustainable alternative, emphasizing a regenerative system that minimizes waste.

The World Economic Forum [1] has specified that CE principles are essential for preserving our current way of life by decreasing natural resource utilization and allowing the earth sufficient time to replenish its resources. Key principles of the CE include [2–8]:

1. Extending Product Life Cycles: CE encourages practices that maximize the lifespan of products, ensuring they remain in use for as long as possible.

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2. Resource Efficiency: CE seeks to optimize resource utilization, minimize waste, and reduce the extraction of virgin materials.
3. Promoting Reuse, Repair, and Recycling: Circular practices emphasize reusing products, repairing them when necessary, and recycling materials to create new products [26].

However, different stages in the lifecycle of buildings requires different stakeholders.

1.2 Stakeholder Theory

In the context of stakeholder theory, understand the type and role of stakeholders is critical. A stakeholder is defined as any group or individual who can impact or be impacted by the objectives of an organisation [9] or a focal issue [10], such as the transition to a CE. Particularly, when targeting stakeholder engagement activities and impacts of stakeholder relations, it often implies a specific approach, which may be moral, strategic, and/or pragmatic [11, 12].

1.3 Stakeholder Analysis

Previous research has presented various findings on stakeholder roles and interests in a CE. For example, Govindan and Hasanagic (2018) highlighted that, when establishing circularity in supply chains, governments play an important part by promoting circularity through laws and policies sympathetic to the goal [13].

Marjamaa et al. (2021) examined stakeholders' joint sustainability interests while Geissdoerfer et al. (2017) stated that in a CE, governments, companies and Non-Governmental Organisations (NGOs) play key roles as agents driving systemic change [14, 15]. It is widely accepted that the support of all stakeholders is needed when implementing a CE on a large scale [16].

Stakeholder analysis is a crucial process in business that helps organizations understand and manage their relationships with various stakeholders. A stakeholder is any individual, group, or organization that has an interest in, is affected by, or can influence a company's activities and decisions. Stakeholders can be internal (such as employees and shareholders) or external (including local communities, regulators, and environmental groups). Their concerns and interests range from financial returns and employment opportunities to regulatory compliance and environmental protection. Stakeholder analysis is the process used to identify and assess the importance, influence, interests, or impact of various stakeholders in relation to a project or business decision. The primary objective is to ensure that the needs and opinions of stakeholders are considered, allowing for better decision-making and effective management of potential conflicts or issues. The typical steps in Stakeholder Analysis include [17, 18]:

1. Identify Your Stakeholders:
   - o Create a comprehensive list of all individuals and groups who may impact or be impacted by your project.
   - o Ensure all affected parties are recognized and duly considered.
2. Understand Your Stakeholders:
   - o Identify the issues that matter to them, along with their expectations and needs.

3. Group Your Stakeholders:
   o Classify stakeholders according to their levels of interest and influence.
   o Strategically target your engagements based on this classification.
4. Evaluate Key Stakeholders:
   o Identify stakeholders with the most interest and influence in your project.

Stakeholder analysis ensures that stakeholder needs and opinions are considered, leading to better decision-making. Effective stakeholder management helps prevent conflicts and improves project outcomes.

2 Purpose of This Study

Various stakeholders assume specific roles in Circular Economy Management in real estate, shaping the sector's value chain. They include suppliers and raw material providers, manufacturers and producers, distributors and retailers, consumers, waste management and recycling industry, and reverse logistics and circular service providers [15]. Significantly, real estate developers and facility managers are focusing on expanding the building's value chain and optimizing facility services for better operational efficiency. From the above argument, we hypothesize that:

Hypothesis 1 (H1): The adoption of CE principles is positively and significantly correlated with influences from organizational (a), regulatory (b) and community (c) stakeholders.

Although companies mostly adopt CE principles in the quest to enhancing competitiveness and sustainability performance [15], adopting them also robustly contribute to stakeholder satisfaction. According to Orlitzky (2011), responding to stakeholder demands or pressures creates a sense of trust and loyalty. The authors further explained that high satisfaction and reputation from stakeholders are strategically advantageous, in that, it has been shown to positively influence market and financial performance [19–22]. Adoption and implementation of CE principles influence stakeholder satisfaction from internal and external perspectives because orientation towards such eco-effective initiatives positively aligns with stakeholder desires and interest which is protection and preservation of natural resources as well as the Earth [19]. Integrating CE principles into business processes and practices will promote the recovery, reuse, recycling and repurposing of materials and energy to benefit the natural environment. Such company practices as indicated by Yang and Wu (2016) [23] lead corporations to achieve green legitimacy with stakeholders. It is worth noting that green legitimacy originates from high levels of external stakeholder satisfaction as exposed under institutional theory. According to Ünal et al. (2019) [24], the institutional theory indicates that companies attain legitimacy when external stakeholders are satisfied with or perceive that the practices and actions of the firm are appropriate and acceptable. Thus, this study seeks to contribute to understanding the interactions between CE principles, key partner and key customer stakeholders. From the discourse, we hypothesize that:

Hypothesis 2 (H2): Adoption of CE principles will positively and significantly influence key partner (a) and key customer (b) stakeholder as well as sustainable businesses (c).

Based on stakeholder and institutional theories, meeting stakeholder needs enhances a company's legitimacy [25]. Yang and Wu [23] note that satisfying stakeholders with sustainable practices leads to 'environmental legitimacy.' In Circular Economy (CE) initiatives, this satisfaction builds trust and a positive reputation for the company [19, 26, 27]. Consequently, the company gains 'green legitimacy,' as per Yang and Wu [23], which brings market, social, and financial benefits, reduces risks, and improves performance. Hence, we suggest the following hypothesis:

Hypothesis 3 (H3): Sustainable legitimacy is positively and significantly influenced by key partners (a) and key customers (b) stakeholders.

Below is the research model of the study and the hypothesized relationships with regard to influence and interest (Fig. 1).

3 Methods

The research approach is drawing upon real estate development projects as case studies. These were characterized in their role and placed in the map the different stakeholders according to their role in the value creation along their interest and their influence as described by [9]. Then it places the stakeholder in the stakeholder analysis matrix shown in Fig. 1.

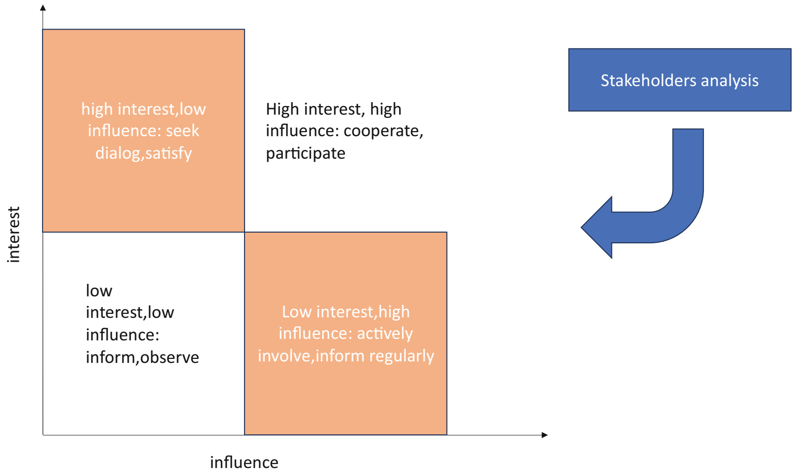

Fig. 1. Stakeholder analysis matrix methodology, developed from [9].

4 Results

A range of new value creation stakeholders were identified and analysed to which extend their role is defined in traditional business models. The key benefits for owners and real estate investors comes from the adaptability to changing market demands, re-use and repurpose, low impact on urban ecology and biodiversity, innovative new real estate products among others.

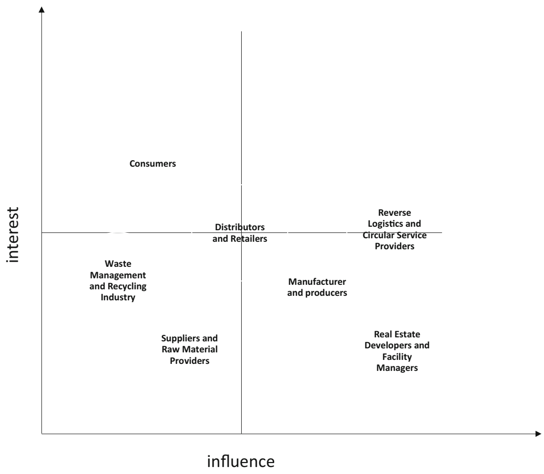

Fig. 2. Stakeholder analysis along the lifecycle.

We analysed the whole building life cycle and identified various stakeholders through the value chain (Fig. 2).

1. **Suppliers and Raw Material Providers**: These stakeholders play a crucial role in sourcing sustainable materials and minimizing waste. Their decisions directly impact the circular value chain.
2. **Manufacturers and Producers**: Circular design principles guide their product development. By creating durable, repairable, and recyclable goods, they contribute to circularity.
3. **Distributors and Retailers**: Educating consumers about circular choices and promoting circular products are essential roles for these stakeholders.
4. **Consumers**: Their choices-whether to reuse, repair, or recycle-directly impact the circular system.
5. **Waste Management and Recycling Industry**: These stakeholders ensure that materials are repurposed, reducing the need for virgin resources.
6. **Reverse Logistics and Circular Service Providers:** They manage the return journey where materials and components are reused, recycled, and returned in a reverse process, addressing the needs of the construction industry.
7. **Real Estate Developers and Facility Managers**: They focus on circular building designs, adaptability, and minimal ecological impact within the built environment.

4.1 Suppliers and Raw Material Providers: Architects of Sustainability

Suppliers and raw material providers are the foundation of circularity. Their sourcing decisions create a domino effect throughout the value chain. Choosing sustainable materials, minimizing waste, and adopting closed-loop practices, they trigger value creation. Consider the case of Patagonia, a renowned outdoor clothing brand, as an example. Patagonia's commitment to using recycled materials in their products not only reduces waste but also serves as a model for other suppliers [28].

4.2 Manufacturers and Producers: Crafting Circular Narratives

Manufacturers and producers wield considerable power. Beyond production, they shape product design. Circular design principles-durability, repairability, and recyclability-become their guiding stars. Their innovations ripple across industries, influencing consumption patterns. One good example is Interface, a carpet tile manufacturer. Interface's "Mission Zero" initiative aims to eliminate any negative impact on the environment by 2020. Their modular carpet tiles are designed for easy replacement and recycling, promoting circularity [29].

4.3 Distributors and Retailers: The Circular Bridge Builders

Within real estate, distributors and retailers act as critical connectors to bridge the gaps between production and end-use. Educating both property owners and end-users about circular choices-whether through labeling, incentives, or storytelling—fuels value creation. Consider the efforts of Unilever, a global consumer goods company. Unilever's "Love Beauty and Planet" brand focuses on sustainable beauty products. Their packaging clearly communicates recyclability, encouraging consumers to participate in the circular loop [30].

4.4 Consumers: The Silent Revolutionaries

Consumers, often underestimated, have a significant influence. Their choices echo through supply chains. Adopting circular practices—repairing, reusing, and recycling—they nudge the system towards sustainability. Education and awareness empower their decisions. The "Buy Nothing" movement, showcasing goods sharing and exchange in communities, is a prime example of consumer-led circularity [31].

4.5 Waste Management and Recycling Industry: Guardians of the Loop

Waste management and recycling professionals are unsung heroes. They recover materials, divert waste from landfills, and revitalize discarded resources. Their role extends beyond collection; it's about closing loops and conserving finite resources. The Ellen MacArthur Foundation's "Circular Economy 100" program brings together companies, including Veolia and SUEZ, to collaborate on circular waste management solutions [32].

4.6 Reverse Logistics and Circular Service Providers: The Return Journey

Reverse logistics—product returns, refurbishment, and remanufacturing—finds purpose in circular service providers. They orchestrate the return ballet, ensuring products re-enter the value chain. Their innovations—think circular leasing and sharing models—redefine consumption. For instance, the "Rent the Runway" platform allows users to rent high-end fashion items, extending their lifecycle and reducing overall waste [33].

4.7 Real Estate Developers and Facility Managers: Building Circular Foundations

Real estate developers and facility managers wield influence over the built environment. Circular buildings—designed for adaptability, longevity, and minimal ecological impact—become their canvas. From repurposing spaces to integrating circular services, they redefine value. The "CIRCL" building in Amsterdam, developed by ABN AMRO, exemplifies circular principles with its modular design, recycled materials, and energy-efficient features [34].

5 Conclusions

This study is a pioneering exploration of the stakeholders in value creation. It shows the benefits of encouraging stakeholders to actively engage in the co-creation and co-innovation of circular solutions. This involves identifying different stakeholders in the design and development of strategies, policies, and projects related to the CE. By defining their new role, a variety of business models, and innovative and effective solutions can be developed.

Stakeholder analysis is equally relevant in the context of CE projects, aimed at creating sustainable and regenerative systems. CE projects seek to minimize waste, promote resource efficiency, and establish closed-loop systems. Effective engagement of stakeholders is crucial for their success.

Thus, it became clear that understanding stakeholder interests is crucial. Another key aspect is the Life Cycle Approach and Material Flows, as CE projects require comprehensive accounting of material and energy flows from cradle to cradle. Multi-Stakeholder Collaboration is also vital, since CE solutions demand collaboration among various stakeholders. For example, Public-Private Partnerships (PPPs) enhance government spending capabilities by overcoming legal, regulatory, and institutional barriers. Lastly, transitioning toward a CE requires a corporate culture shift, aligning economic, social, and environmental dimensions.

In summary, stakeholder analysis in CE projects involves understanding diverse interests, fostering collaboration, and considering material flows throughout the lifecycle. Effective stakeholder engagement can drive positive change and foster more sustainable systems. We can state that the adoption of CE principles is positively and significantly correlated with influences from organizational (a), regulatory (b) and community (c) stakeholders (H1).

The significance of stakeholder engagement is increasingly recognized, particularly for its role in supporting the success of a CE model and in fostering the a culture of sustainability, which is broadly defined in this study. Indeed, positive stakeholder relationships are essential for long-term value creation; they enable a company to listen to and engage with relevant stakeholders as well as to disseminate values and principles aimed at safeguarding all dimensions (economic, social, and environmental). Consequently, the adoption of CE principles is expected to have a positive and significant influence on key partner (a) and key customer (b) stakeholders as well as on sustainable businesses (c). (H2).

Stakeholder engagement in transitioning to a CE fosters relationships based on consent, trust, and shared responsibilities, aligning with sustainability principles and positive behaviors. In this context, engaging key actors through proactive, inclusive, and integrated approaches is crucial for safeguarding ecosystems and shifting toward approaches emphasizing not only the economic outcomes, but also the environmental and social ones, adopting a long-term view. Thus, the commitment and willingness to improve all the dimensions impacted by a company's activities depend on its cultural framework and the recognition that optimizing economic performance is closely linked to environmental and health protection. In conclusion, sustainable legitimacy is positively and significantly influenced by the involvement of key partners (a) and key customers (b) stakeholders. (H3).

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Analysing Stakeholder Opinions Within the COST Action CA21103 CircularB and Beyond: Circular Economy Implementation in Construction

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Abstract. This study examines the importance and adoption of circular economy (CE) principles within the construction industry by focusing on stakeholders' opinions on key CE strategies across different building life cycle stages. The study draws insights from the perceptions of European-based stakeholders who actively participated in the CircularB Workshop 1 Part 2, entitled Creating a Roadmap towards Circularity in the Built Environment - State-of-the-Art. The research comprises two parts. In the first part, a structured survey was employed to systematically collect opinions on the levels of awareness and variations among the adoption and importance of selected CE implementation strategies within the construction sector. The second part engaged stakeholders in a dynamic creative thinking activity, posing seven targeted questions allowing participants to offer multiple answers for each query. Overall, the study sheds light on the multifaceted challenges and opportunities inherent in fostering CE within the construction domain by highlighting the significance of recognising and addressing systemic barriers within the CE framework, the importance of product design for disassembly, and the efficient production of reusable and recyclable materials. Furthermore, it emphasises the necessity to motivate industry stakeholders to participate actively in the transition to a CE, bridging the gap between theory and practice frameworks and increasing the engagement of policymakers and governments.

Keywords: Circular Economy · Construction Industry · Stakeholder Perspectives · Building Life Cycle · Policy Recommendations

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1 Introduction

The concept of circular economy (CE) is gaining global prominence, particularly in European policy development, where it is now integrated into legal frameworks and national strategies of several European countries, including Spain, Italy, and the Netherlands [1, 2]. Despite widespread efforts encompassing numerous initiatives and programmes introduced to enforce the transition from the conventional linear economic model to a circular approach, the construction sector hardly welcomes innovations, notwithstanding technological advancements [3]. Among different barriers existing in the construction sector to CE development, one of the most critical challenges is linked to the limited involvement, interest, and awareness of stakeholders [4–6]. Recognising the importance of stakeholder involvement in mitigating risks and shaping effective business models, particularly in the context of CE practices, various forms of engagement become crucial [6]. However, a notable challenge is the lack of stakeholder awareness and motivation towards CE, highlighting the need for more inclusive participation [7].

The increasing risks associated with urban challenges, such as climate change adaptation and mitigation, alongside rigorous legislative measures promoting sustainable consumption and production, as well as growing customer interest in environmentally friendly practices, show the necessity of transitioning towards CE practices [8, 9]. In this context, CE drives the construction industry towards adopting innovative and sustainable models, such as green and circular buildings, aligning with environmental objectives and offering long-term economic benefits. Consequently, collecting a comprehensive understanding of stakeholders' perspectives towards CE is essential to effectively implement and maximise the potential of the CE business models. This involves recognising their perceptions, concerns, motivations, and expectations, ensuring a smooth and effective transition to CE systems.

This study aims to understand stakeholder perspectives on CE within the construction industry through two approaches: 1) assessments from a stakeholder survey and 2) insights from a creative thinking workshop using the Six Thinking Hats method. These activities were performed during the workshop of the European COST Action CircularB (CA21103) Workshop 1 Part 2 (WS1P2), providing valuable insights into stakeholders' attitudes and perceptions towards CE in construction. The workshop was held in Cordoba, Spain, between 12 to 15 September 2023.

2 Methods

2.1 COST Action CA21103 CircularB and Its Series of Workshops and Activities in Cordoba, Spain

COST Action CA21103, entitled Implementation of Circular Economy in the Built Environment (CircularB), is a four-year networking initiative that started in October 2022. The primary goal of this Action is to develop a comprehensive circularity framework for new and existing buildings, supporting decision-makers and involved stakeholders in assessing the implementation status of the European Circular Economy Action Plan (CEAP). CircularB Action unites a multidisciplinary group of stakeholders from 39 countries, with a predominant representation from Europe. WS1P2 was an integral activity during the inaugural year of CircularB. It encompassed presentations, discussions and interactive activities on various CE-related topics within the context of buildings and built environments, including circularity criteria and KPIs (key performance indicators), circular business models, standards and legislations promoting or hindering circularity. Additionally, the discussions delved into circular feedback value chains, exploring stakeholder interactions and roles. WS1P2 served as the focal point for the survey activities outlined in this study. CircularB members and specially invited local stakeholders actively participated in these survey activities, contributing valuable insights to further the goals of the Action.

2.2 Survey Instrument

A survey instrument was developed to measure stakeholders' opinions on CE strategies in construction projects. Strategies were grouped under four life cycle stages (LCS) and presented in a concise manner. Nineteen items were listed and asked. Participants completed the survey using the semi-guidance structure provided by the authors. The survey questionnaire was organised into three sections: socio-demographic parameters, importance, and adoption levels. Figure 1 lists the selected CE implementation strategies under their LCS.

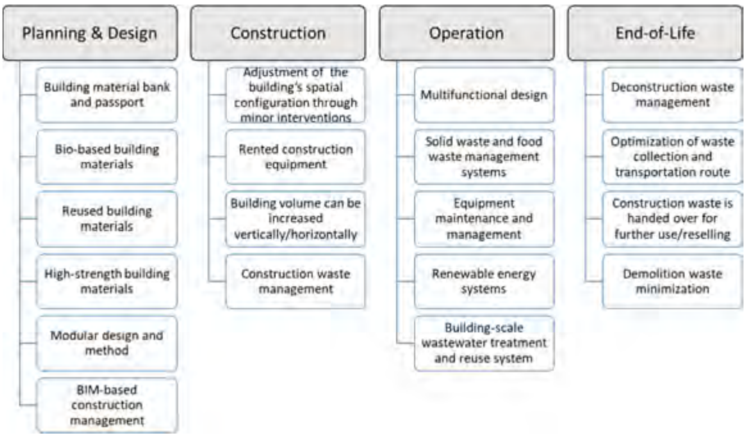

Fig. 1. Selected CE implementation strategies.

2.3 Creative Thinking Activity

On 15th September 2023, the First CircularB Stakeholders Day was held as part of the WS1P2 activities, featuring a dynamic debate that used Mentimeter, an interactive survey tool, to gather and present real-time responses. The debate was enriched by the Six Thinking Hats methodology [10, 11], which explored diverse perspectives arising from the responses to seven Mentimeter Questions (hereinafter, MQs). The questions investigated policies and initiatives related to CE in Construction and Demolition Waste (CDW) and the adoption process of CE in the built environment. The most highly rated or popular responses were discussed after the online collection of feedback, and valuable insights were extracted from the data. This methodology provided a multi-dimensional perspective on the challenges and opportunities associated with CE in CDW, advancing the study in this domain.

3 Results and Discussions

3.1 Stakeholders' Opinions on the Importance and Adoption Levels of CE Strategies

This study summarises the methodology and findings derived from workshops and activities conducted as an integral part of the CircularB COST Action, *i.e.*, mainly from WS1P2. The primary objective was to investigate stakeholders' perspectives regarding key CE strategies within the building sector and the built environment.

Firstly, a semi-guided survey centred around the importance and adoption analysis was employed to gather insights on CE strategies. This survey first gathered information on respondents' nationality, expertise, company size, and stakeholder category. Then, the stakeholders' opinions on the ranking 19 key CE strategies were collected. The distribution of stakeholders by occupation is summarised in Table 1.

Table 1. Summary of the stakeholders' profile.

Stakeholder type	#
Academician/Researcher	29
Contractor	2
Designer Architect and/or Engineer	4
Government and/or Councillor	1
Manufacturer	3
Urban designer	1
Other, please specify	2
Total	42

The stakeholders in the event primarily belonged to the academic domain. However, there are also individuals directly involved in the construction sector industry, including manufacturers, engineers, designers and contractors, consulting companies, and government-level policy and decision-making processes related to the implementation of CE in the construction value chain, particularly in buildings and the built environment. Participants were mostly from Europe, and specifically from Spain, being the dominating country in terms of numbers as the local host of the event. Typically, the participants were experienced individuals with more than five years of active engagement in CE-relevant practices.

The survey responses were analysed to measure the opinions on CE implications across LCS, opinions on CE implementation strategies, and considerations specific to stakeholders' countries. The results highlighted the importance of bridging the gap between theory and practice by motivating industry stakeholders to actively participate in the transition to CE. Although the majority of stakeholders acknowledged the importance of implementing CE strategies throughout the building lifecycle, there exists a disparity between the perceived importance and actual adoption levels, particularly concerning the end-of-life stage. This stage was identified as the most crucial, with a significant gap in the adoption of end-of-life strategies on the ground.

This conclusion gained further support when examining the correlations among key CE strategies' importance and adoption levels. The averages of the Planning and Design, Construction, Operation, and End-of-Life stages for the importance and adoption scores are given in Table 2.

Table 2. The average scores for implementing CE strategies across building lifecycle stages, measuring both importance and adoption by country.

Country	Adoption				Importance			
	Planning & Design	Construction	Operation	End-of-Life	Planning & Design	Construction	Operation	End-of-Life
Austria	2.8	3.4	4.2	3.8	4.0	4.2	4.8	4.3
Croatia	–	–	–	–	4.3	4.4	4.4	4.8
Czech	2.5	2.8	4.4	3.8	4.5	4.6	4.6	5.0
Denmark	2.2	1.9	2.9	2.9	4.0	4.1	3.6	5.0
Greece	2.3	2.4	2.0	1.0	4.2	4.3	4.2	4.6
Italy	3.0	4.4	3.0	3.0	4.3	3.9	4.2	4.0
Latvia	3.2	3.5	3.5	3.8	4.3	4.3	4.3	4.0
Lithuania	3.7	4.2	4.3	4.8	3.2	3.3	3.2	4.5
Luxembourg	2.8	–	–	–	4.3	3.8	3.6	4.0
Malta	2.0	2.0	2.4	4.3	4.7	4.5	4.9	4.3
North Macedonia	3.1	3.3	3.3	3.1	4.3	3.8	4.3	4.4
Portugal	2.6	3.1	3.6	3.3	4.5	4.6	4.8	4.8
Romania	4.0	3.4	2.8	1.8	4.5	4.6	4.0	5.0
Serbia	2.8	2.9	2.1	2.0	4.2	4.4	4.8	5.0
Spain	2.5	2.8	2.9	2.3	4.1	3.7	4.1	4.7
Turkey	1.9	3.1	3.3	3.2	4.1	4.3	4.3	4.7
United Kingdom	2.2	3.0	2.0	1.5	4.5	4.2	4.4	4.8
Average	2.7	3.1	3.2	3.0	4.2	4.1	4.2	4.6

Notably, strategies such as deconstruction waste management, optimisation of waste collection and transportation routes, construction waste handling for further use/reselling, and demolition waste minimisation exhibited substantial gaps, requiring increased investment and attention to facilitate their practical implementation.

The survey also indicated that strategies such as building-scale wastewater treatment and reuse systems, modular design and methods, high-strength building materials, and multifunctional design had achieved adequate implementation levels relative to their perceived importance.

Some participants - i.e., three academicians and two manufacturers - did not provide scores for adoption levels, citing a lack of knowledge about the practical situation. This highlights the urgent need to bridge the gap between theory and practice.

Stakeholder scores from various countries were analysed for insights into construction project life stages, with average scores shown in Fig. 2.

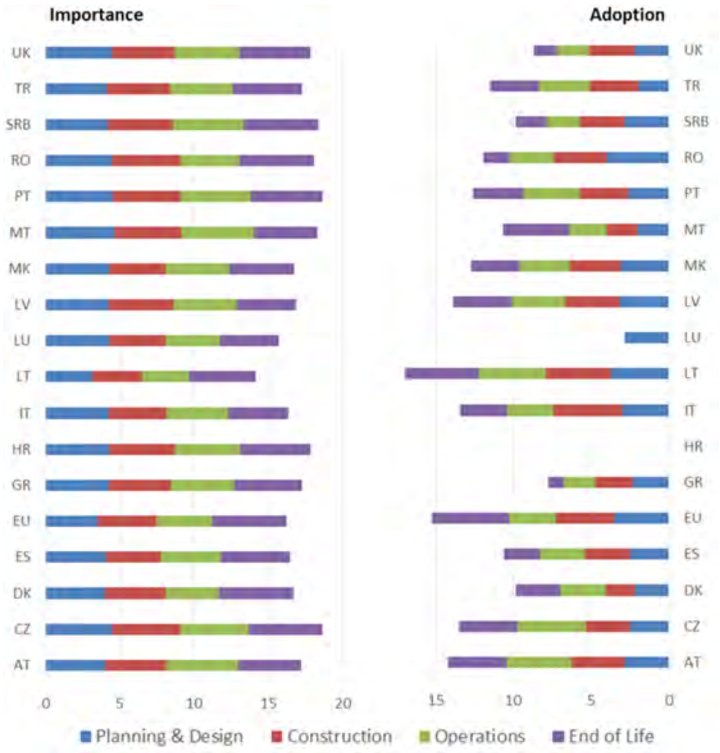

Fig. 2. Average values of the stakeholder responses from participating countries for the CE implementation strategies for their importance and adoption.

Some stakeholders, like Croatia, didn't score certain stages due to a lack of expertise. European policymakers were represented as the 'EU'. Stakeholders from the Czech Republic, Portugal, Croatia, Serbia, and Malta rated the highest importance, while Lithuania and Luxembourg were the lowest. Nine countries, including Turkey and Romania, had higher adoption rates. Interestingly, stakeholder opinions varied; German stakeholders rated implementation strategies important but low on adoption, whereas Lithuania scored high on adoption but low on importance.

Zhang et al. [12] ranked European countries on mineral landfilling, with Lithuania at the top and Spain, and Romania at the bottom, matching our adoption rankings. However, Greece and the UK, lower in our study, ranked higher in theirs.

At a country level, Czech Republic, Portugal, Croatia, Serbia, and Malta scored the highest in terms of importance levels, while Lithuania and Luxembourg scored the lowest. Regarding adoption levels, noticeable divergences were observed across most participating countries compared to their importance levels. Out of all the European countries, it is surprising to note that Germany and the UK had the lowest scores when it comes to the adoption of CE practices. This is despite the fact that they have better overall performance compared to other countries in Europe. On the other hand, Lithuania emerged as the leader with a high adoption score of 4.2, which is slightly higher than "important". However, it is still hard to comprehend why Germany and the UK performed poorly in terms of adoption, as they are both highly developed countries with advanced economies.

When we look at Lithuania's stakeholders, we see that they have the highest adoption scores but the lowest importance levels. This is a paradox as the country has been consistently progressing year after year, and they have shown remarkable improvement in their CE indicators [13]. It is difficult to explain why the stakeholders in Lithuania have a low perception of the importance of CE practices despite their impressive adoption scores. Further research and analysis are needed to understand this phenomenon better.

The adoption scores for both "end-of-life" stages were the lowest in Germany, the UK and Romania, with averages of 1.0, 1.5, and 1.8, respectively. It is understandable to see the low score in Romania, as it is listed as the lowest-scoring country in Europe's circularity ranking [14]. However, Germany and the UK are among the leading countries in CE-related publications and have achieved excellence with advances in the construction industry that promote efficiency and sustainability [15]. For instance, the UK, as a territory with a huge quantity of inert raw materials, imposes an Aggregates Levy - a tax on sand, gravel and rock that is dug from the ground or dredged from the sea in UK waters - to encourage the use of secondary materials. Despite the high level of performance and importance given to CE in Germany and the UK, this lower adoption score of "end-of-life" practices might be related to the legislative framework, which is mainly moving towards the elimination of landfilling through increased taxes: *e.g.*, specific bans or taxes to increase the fees of landfills. The high cost of landfill tax may encourage stakeholders to prefer other types of waste destinations, particularly for end-of-life waste [16]. This situation requires a more in-depth analysis, and conducting in-person interviews with stakeholders may be necessary for better justification.

The operation stage had the highest average adoption score of 3.2, but this was not significantly different from the other scores given for the other life stages. For instance, the minimum average adoption score was calculated for the planning and design stage at 2.7. All the scores for the adoption levels were around 3.0, indicating neutrality. The stakeholder ratings for the adoption of CE implementation strategies were analysed, and it was found that the average scores were the lowest for the Design and Planning stage. In particular, the strategies related to "bio-based building materials" and "building material bank and passport" received the lowest average scores of 2.27 and 2.53, respectively. This result indicates that there is a need to focus more on these aspects during the Design and Planning stage. Additionally, the recent literature supports the findings that circular design principles, such as modular design, have been promoted in the construction industry. However, there have been fewer attempts to implement these principles during the Design stage. This low adoption is mainly due to the complexity of building multiple lifecycles and the unsuitability of certain building components for this design concept, as noted by Yang et al. (2022) [17]. Therefore, we highlight the necessity to create awareness about the benefits of circular design principles and encourage their implementation during the Design stage.

Participants agree that the circularity concept does not accelerate key CE strategies. This may indicate the sector is influenced by other concepts like "sustainability", "resource efficiency", "waste management", and "green building". Despite circularity's growing awareness, with its importance scoring around 4.5 (between "important" and "extremely important"), its diffusion remains "neutral". This shows a limited shift towards circularity in practices and projects. It's crucial to note that European sectors' circularity performance is influenced by concepts overlapping with CE. Thus, enhancing understanding and showcasing the benefits of circularity is key to its broader adoption across sectors and industries.

Unfortunately, there is a widespread lack of comprehension regarding the precise meaning of circularity and its principles in many countries, which poses a major challenge to the development of proper supporting policies for CE strategies. This fact spotlighted the pivotal role of governments, policy-making bodies, and institutions in steering the transition to a CE in the construction sector. Concurrently, numerous initiatives across countries aim to promote CE implementation, with notable examples highlighted, particularly in the UK and Spain.

3.2 Six Thinking Hats

The second activity, conducted using Mentimeter as a guiding tool along with the Six Thinking Hats method, engaged 24 stakeholders through seven proposed questions (Fig. 3), allowing participants to offer diverse answers for each query. Although this activity encompassed various stakeholder types and multiple industry sectors, a majority hailed from academia. On the front of policies and legislation, the prevailing policies predominantly focus on waste management and recycling.

The activity facilitated a discourse on the impediments to CE implementation, with stakeholders underscoring the deficiency in legislation and policies as a primary barrier. Other obstacles identified included costs and the need for proper education. Participants proposed indicators for monitoring the transition, predominantly focusing on end-of-life indicators for recycling, reuse, and CDW management, albeit with minimal consideration for social factors. Crucial future steps to enhance CE implementation in the sector involve increased engagement of policymakers and governments, adopting digital tools and technologies, illustrative case studies showcasing the technical and economic viability of CE solutions, heightened awareness, and establishing standards and incentives.

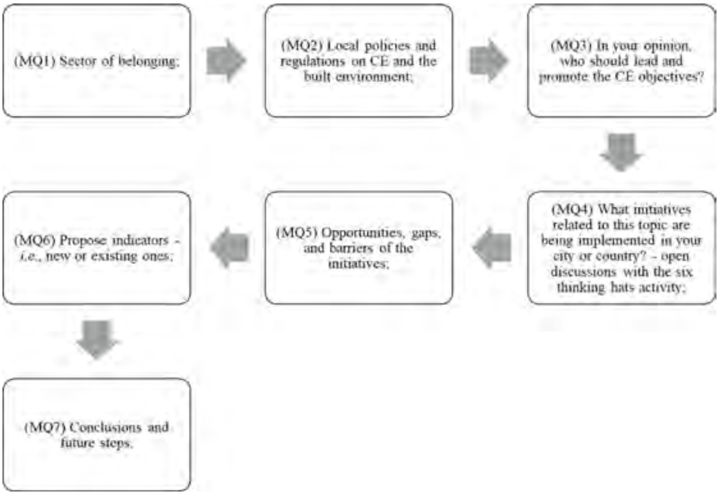

Fig. 3. Seven questions and steps of the creative thinking activity.

4 Conclusions

In conclusion, this research highlights the importance of gaining a deeper understanding of stakeholder perspectives on various aspects of CE within the built environment. To achieve this, it is necessary to conduct further research by increasing the sample size and diversifying respondents in the survey. The methodology employed in this study for ranking and prioritising key CE strategies needs further refinement through an exhaustive literature review, including stakeholders' input on crucial strategies not covered in the initial survey. A more comprehensive evaluation of circularity performance in buildings can be achieved by transforming the ranking and prioritisation into a multi-criteria model that encompasses technical, economic, environmental, and social dimensions. This will provide a more holistic perspective on the sustainability of buildings.

Overall, the findings highlighted the significance of systemic barriers in the CE, product design for disassembly, the role of packaging processes in generating CDW, and the efficient production of reusable and recyclable materials. Furthermore, the conclusions highlighted the imperative of bridging the gap between theory and practice by motivating industry stakeholders to participate actively in the transition to a CE. Finally, increasing the engagement of policymakers and governments, adopting digital tools and technologies, illustrative case studies showcasing the technical and economic viability of CE solutions, heightened awareness, and establishing standards and incentives are crucial future steps to enhance CE implementation in the sector.

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6D-BIM Applications to Enrich Circular Value Chains and Stakeholder Engagement Within Built Environments

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Abstract. Building Information Modelling (BIM) is a digitalisation tool that is widely adopted in construction industry. It is a three-dimensional digital replica of asset(s) such as buildings, which contain architectural information and building details (e.g. dimensions, materials, parts, and components). It has evolved from 2D CAD models (or blueprints) in the past to 3D CAD models embedded with information layers (e.g., construction time sequence or 4D-BIM), resulting in automation in construction. BIM has now been essential in various countries; for example, new UK BIM standards require asset owners to keep and maintain building information. BIM adopts an interoperable concept that can benefit the whole life-cycle assessment (LCA) and circularity of the built environments. Its applications extend to six dimensions (6D) where time sequence, cost and carbon footprint can now be reported in real time. These attributes are essential to stakeholders and critically help reduce any unexpected consumption and waste over the life cycle of a project. This study builds on the development of 6D BIM of an existing building to enrich circular value chains and stakeholder engagement. This paper highlights the development of 6D BIM, and, subsequently, the stakeholder interviews to address challenges, barriers, benefits, and effectiveness of 6D-BIM applications for stakeholder engagements across circular value chains. Snowballing sampling method has been used to identify stakeholder interviews to obtain new insights into the digital valorisation for stakeholder engagement. The outcome of this study will exhibit new insights and practical paradigms for BIM applications in built environments.

Keywords: 6D-BIM · Building Information Modelling · Circular Economy · Value Chain · Stakeholder Engagement

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1 Introduction

Circular economy (CE) is the global challenge that requires a cross value chain transition from linear economy (raw material extraction, production, use, land fill) to regenerative economy (extraction, production, use, reuse/recycling), as illustrated in Fig. 1. CE underpins the regenerative solution to resolve the climate issues by reducing raw material extraction, eliminating/minimising wastes, and then cutting down carbon footprints from raw material extractions and associated environmental impacts. The EU has introduced Circular Economy Action Plan [1], which embraces both the CE action and CE monitoring framework against science-based targets across circular value and supply chains [2]. It is very important to note that CE challenges cannot be resolved in isolation without the cooperation of every sector in every country around the world [3]. The new CE action plan announces initiatives along the entire life cycle of components and assets. It addresses how they are designed, promotes CE practices, encourages sustainable consumption, and aims to ensure that waste is minimised and the resources used are regenerative within the economy for as long as possible [1]. To scale up a widespread transition from linear to circular economy, value and supply chain actors must realise and closely collaborate across sectors for harmonized actions to enhance influence, promote inter-relationship, and overcome the barriers towards circular economy implementation [4]. Consequently, this study investigates the added value and capabilities of building information modelling (BIM) to improve and transform cross-functional stakeholder engagements across circular value chain within built environment sector.

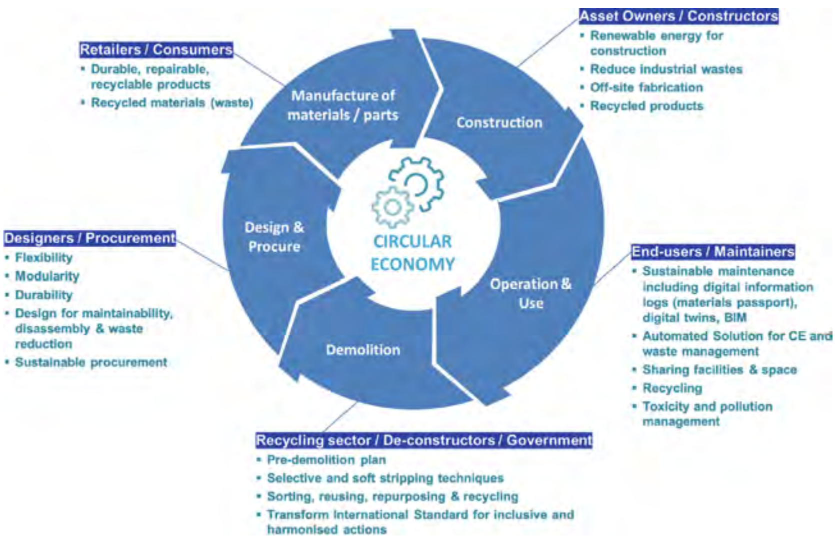

Fig. 1. Circular value chain and lifecycle management practices towards net zero. Stakeholders' interaction across value chain requires visualization and valorisation of data and information.

2 Digitisation Tools and Their Added Values

2.1 Building Information Modelling (BIM)

BIM is a digital platform to collect, create, archive, share and manage inventive data and information that can form 3D architectural model with full-scale dimensions. It can replicate and simulate digital information that is essential for construction, project management, monitoring and operation of a specific asset during the whole lifecycle [5, 6]. BIM embraces a coordinated digital dataset where relevant parties can access, visualize and share the information with respect to manufacturing, design, construction and operation as well as any necessary documents or contracts about the project. The modification or change within BIM environment will be immediately shared among stakeholders in the project or across value and supply chains [7, 8]. BIM (which can evolve to be a digital twin) emphasises the role and influence of all stakeholders within a project or a built environment boundary. It can analyse the capabilities of issues in construction, design, operation and maintenance at the early stages, which provides benchmarking targets for economical, environmental and social values of the assets. BIM is not simply a 3D architectural model but its adoption can make significant changes in resources workflow and project delivery process [9]. Currently, BIM adoption in the UK has been steadily increasing. However, recent requirements for British asset owners/investors to maintain and update building information has raised the importance of BIM and its associated skill training.

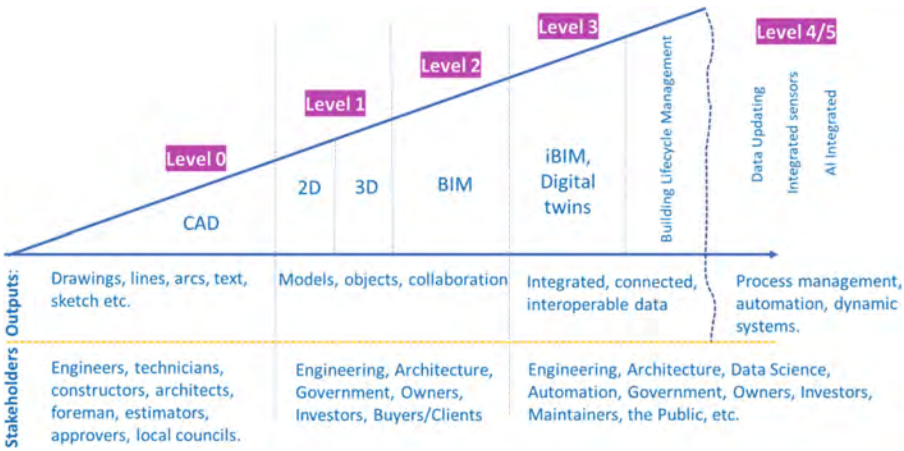

Fig. 2. Evolution of BIM metrics, outputs and maturity across circular value chain stakeholders, modified from [5].

BIM integration across value chain spans throughout the entire life cycle of a project or an asset. As shown in Fig. 2, digitisation evolution can be associated with stakeholders and life cycle stages of an asset (from design, production, construction, maintenance, and operation to deconstruction (or end of life management). Life cycle assessment (LCA) is then an integral part of BIM automation where several well-defined key performance indicators (KPIs) are regularly assessed and monitored in order to justify and benchmark a system's environmental, economic and social impacts (in accordance with EU CE Action Plan [1, 10]). On this ground, BIM can be evolved and improved to enrich the capacity and capabilities to determine various KPIs and enable several stakeholders and cross-functional parties to work collaboratively together and to exchange information in accordance with the BS Standard 19650-1 [8]. Table 1 illustrates the levels of BIM maturity and the classification at each level, which describes the types of collaborative work, tools and technology used to understand the process at each level (adopted from [5]). This displays the capabilities and added values of BIM across scales in practice.

Table 1. Level of BIM maturity and dimensions [5].

Classification	Description of capabilities and added values
Level 0 (CAD)	Unmanaged CAD, in 2D, with paper (or electronic paper or blue print) data exchange
Level 1 (CAD, Solids Work)	Managed CAD in 2D or 3D architectural format with a collaborative tool providing a common data environment with a standard approach to data structure and format. Commercial data separate
Level 2 (BIM)	A managed 3D architectural environment held in separate discipline 'BIM' tools with data attached; commercial data will be managed by enterprise resource planning software and integrated by proprietary interfaces or bespoke middleware. The dimension of information can be further extended to 4D to include construction sequencing and 5D to include cost information associated with the sequence
Level 3 (Digital Twins)	A fully integrated and collaborative process enable by 'web service' or an interactive network (e.g. intranet, cloud, co-simulation, Navisworks link, etc.) and compliant with emerging industry foundation class standards. Generally, at least 6 dimensions (6D) of information will be integrated. In addition to physical dimensions in 3D (width, length, depth), the dimension of information will traditionally include 4D for construction sequencing, 5D for cost information, and 6D for project life-cycle management information or contractual arrangement. An additional information layer (i.e., 7D) can also incorporate carbon footprint, environmental impacts and toxicity information
Level 4 (Digital Twins)	Integration of inspection data (routine condition monitoring) or interactive real-time sensors (sensing for spontaneous actions, transient responses, ambient environments, crowdsensing or live human perceptions) in the BIM/Digital twins
Level 5 (Digital Twins)	Automation for decision making. A full integration of inspection data, real-time sensing data, and co-simulations for predictions (using constitutive and empirical models, numerical or analytical simulation methods, machine learning and artificial intelligence, data-driven physics informed techniques, etc.)

2.2 Demonstration I: 6D-BIM for Carbon Credit Assessment

Demonstration I, as illustrated in Fig. 3, highlights a specific BIM application within the context of railway station buildings using a Revit-based simulation of construction work for King's Cross station in London UK [11]. The 3D architectural BIM further adopts and transforms the King's Cross station building information into a 6D BIM. The 6D model contains a time and cost schedule with carbon emissions calculation, and renovation assumptions using Revit. The economic and environmental impacts can be determined in real time using Application Programming Interface (API). The project's outcome has already been exploited by re-construction stakeholders and asset owners. The carbon estimations in repair and maintenance stage can be reported for carbon offsetting. The BIM also allows future carbon credit calculations by assessing potential replacement options using low-carbon components and materials.

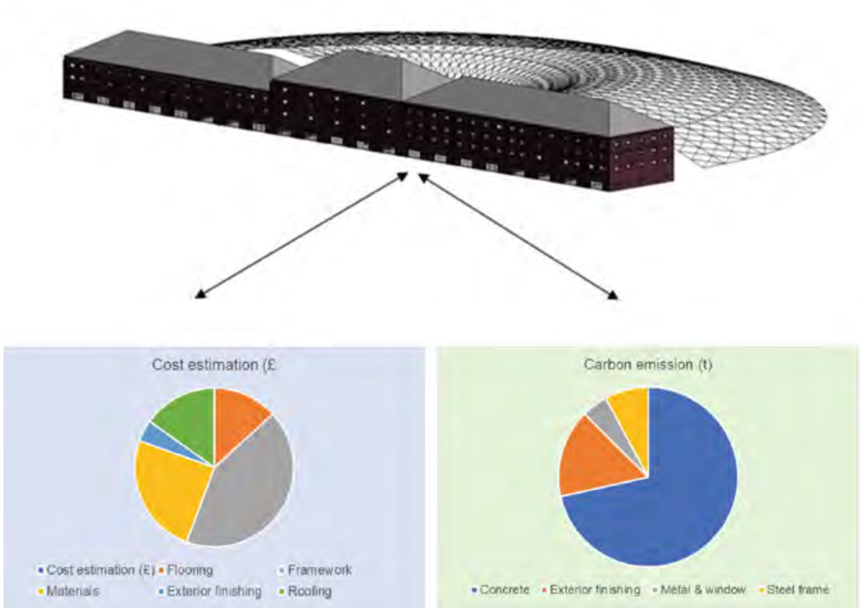

Fig. 3. A digital twin for sustainability evaluation of railway station buildings, adopted from [11]. King's Cross station in London UK has been used to demonstrate the real-time capability of 6D-BIM to determine lifecycle cost, carbon footprint.

2.3 Demonstration II: 6D-BIM for Net Zero Energy Building Improvement

Demonstration II, as displayed in Fig. 4, addresses the capabilities of 6D-BIM for determining technical and financial viability of Net Zero Energy Buildings (NZEB) for 'existing' buildings [12]. A number of suitable options for NZEB solutions can be tested and validated in BIM environments suitable for a specific geographical area. The 6D-BIM has been exploited by the developers to visualize NZEB options, promote collaboration among stakeholders, and accurately estimate associated costs and associated technical issues encountered with producing an NZEB in a pre-determined location. This demonstration also unlocks 6D-BIM capabilities to assess benefit/cost and apply renewable technologies to the existing building to improve energy efficacy.

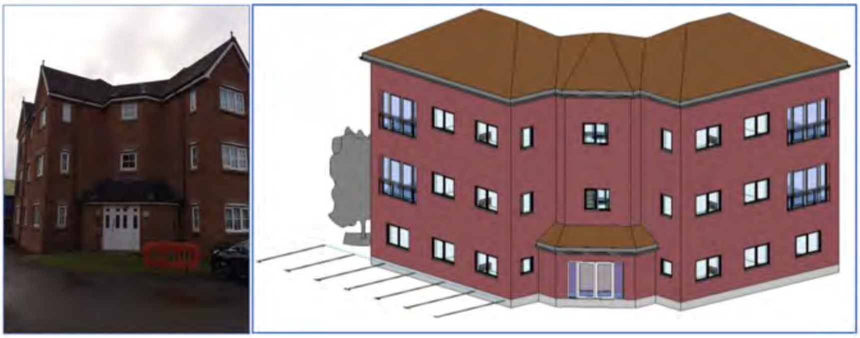

Fig. 4. 6D-BIM of an existing residential building in the UK to implement deep renovation options towards NZEB status, adopted from [12].

3 Methodology

To ensure an integrated approach toward circularity, representative stakeholders of all value chain elements will be invited to participate in closing the loop of supply and demand. Academic and industrial actors' involvement will enable the detection of specific Circular Business Models (CBMs) and related benefits in CE practices. For this purpose, this research adopts a quantitative survey approach using online questionnaires to investigate the effectiveness of BIM in the transfer of information between partners more efficiently, allowing them to develop new insights and make better-informed design choices. Accommodated by the real-world demonstration cases above, the questions have been designed to assess the quality of BIM's digital environment to enrich stakeholder engagement enabling participatory conversations on different aspects and interests necessary to develop viable business model developments focusing on value proposition, customer involvement and supply chain management. The outcome can facilitate an actionable and scalable BIM application and provide stakeholders with a digital monitoring tool for the benefits deriving from CE, as well as tracking CE performance indicators of Circular Business models. The investigation by online surveys will be conducted internationally across all value chain stakeholders. The non-personal data was collected anonymously without withholding personal information. All respondents had given consent for data collection. The data requested in this study was collected and processed by the researchers in accordance with the provisions of Regulation (EU) 2016/679 (the General Data Protection Regulation, GDPR) and all other applicable EU and UK privacy and data protection legislation. This study is GDPR compliant and has been approved by the University of Birmingham's IRB. In this study, 41 respondents in total have been collected from across the globe. The role of stakeholders will be used to classify and rank the responses derived from the online survey. Clear guidance has been provided to respondents, assuring anonymity to all to create a safe, fair, and inclusive environment.

4 Results and Discussion

4.1 Stakeholders and Their Understanding into BIM

BIM has been adopted in construction and architecture for nearly 2 decades in order to collect, create, archive, share and manage inventive data and information with an agreeable level of details (LOD). Accordingly, the public survey has been designed to embrace the BIM capabilities across value chain and lifecycle stakeholders. Figure 5 displays the role of respondents across all value chains. Most of them are in academia (27%), architecture, design and construction (22%), and asset ownership & investment (20%).

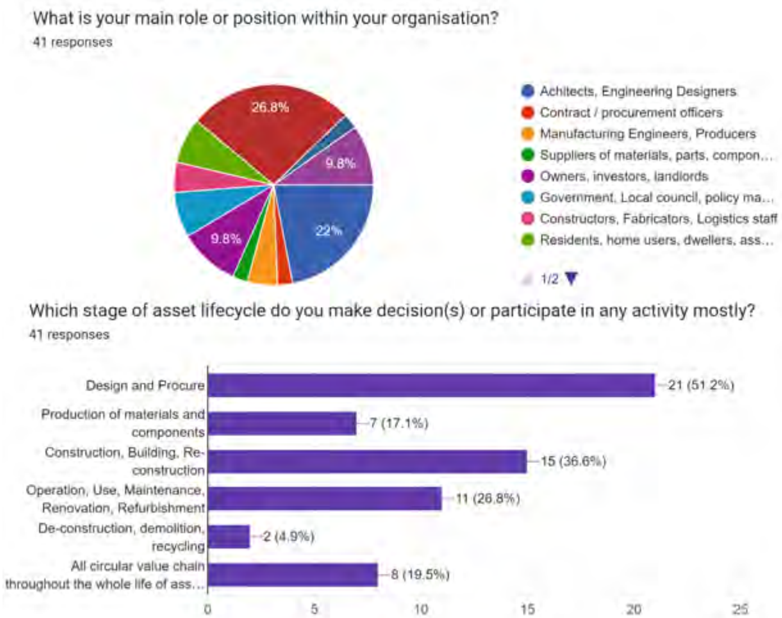

Fig. 5. Classification of respondents within the organisations across value chains.

Our survey results shown in Fig. 6 demonstrate that, in reality, BIM(s) may have been predominantly used in design and construction, but it does not effectively translate its application to engage with other stakeholders across value chains. Clearly, the role of technology enablers (e.g. BIM) in stakeholder engagement is significantly limited (i.e., >20% of response intensity).

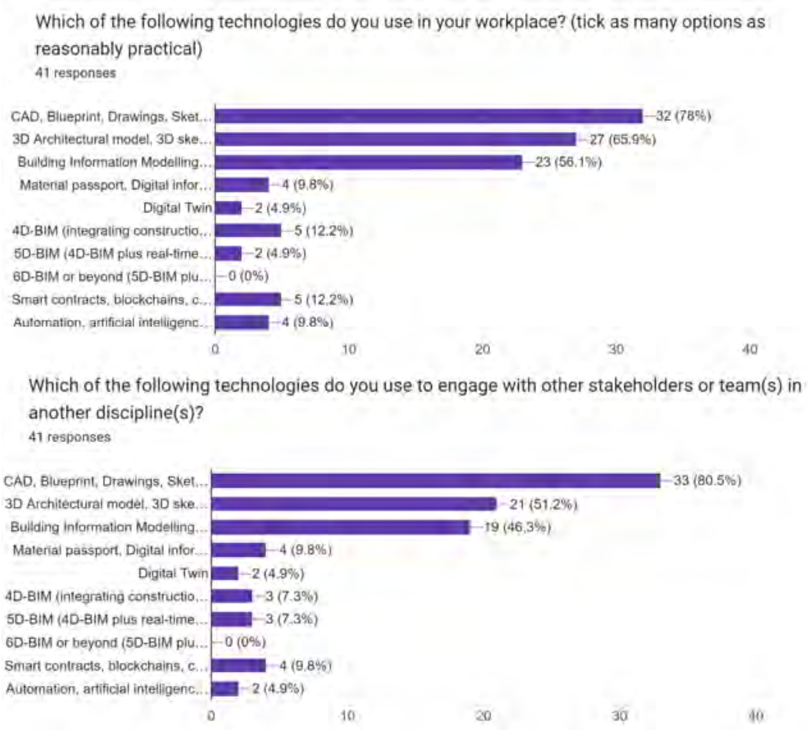

Fig. 6. Role of digitalisation technologies in stakeholder engagement across value chains.

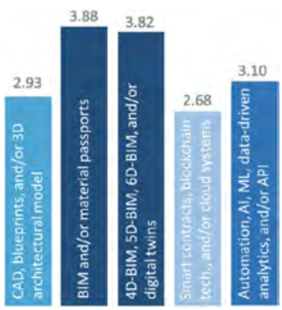

Fig. 7. Effectiveness and quality of digitalisation in stakeholder engagement (ranked out of 5.0).

4.2 Quality of BIM for Stakeholder Engagement

Figure 7 demonstrates the perceived quality and effectiveness of technology enablers in stakeholder engagement. Despite fewer BIM adoptions in practice, the respondents believe that BIM technologies (3D to 6D) can significantly improve the quality of stakeholder engagement. Surprisingly, smart contracts and blockchain do not seem to create added value to stakeholders across value chains. In Fig. 8, the actual BIM applications to enrich circular value chain is still ineffective, especially at the operations and end-of-life stages of lifecycle. This implies that it is necessary for every stakeholder to support and promote research and innovation that improves circular economy practices in sustainable asset management during both operations and end of life phases of lifecycle. The lack of circular economy innovation for existing building stocks is one of the key observed trends derived from the respondents' perception.

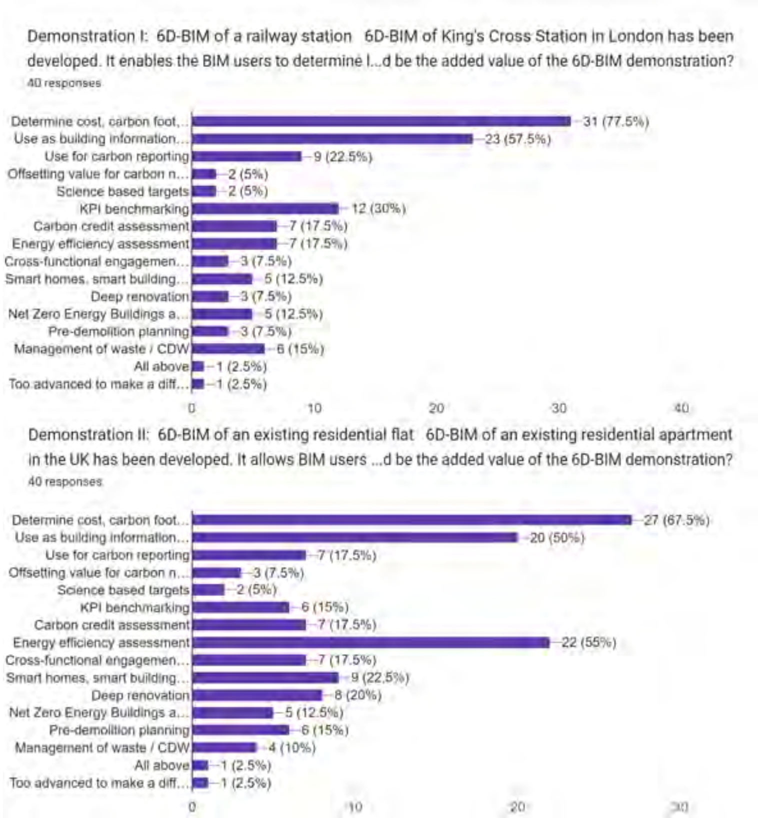

Fig. 8. Perceptions on added value potentials of digitalisation through use-case demonstrations.

5 Conclusion

BIM has been widely adopted in the construction industry, predominantly in architectural design and construction stage. Our study has carefully reviewed the state-of-the-art knowledge related to the application of BIM for stakeholder engagement. It shows a clear gap in the understanding into the quality of BIM to enrich circular value chains and stakeholder engagement. This study has thus conducted the stakeholder survey to identify challenges, benefits, and effectiveness of technology enablers (e.g., 3D to 6D BIMs) for stakeholder engagements. 41 experts worldwide have kindly provided new insights into the digital valorisation for stakeholder engagement. In contrast to market-wide perceptions, our results exhibit that the scale and scope of technology enablers is relatively limited when considering real-life application to enrich stakeholder engagement across circular value chain. This can severely pose the inability to meet net zero targets by built environment sector. All stakeholders must be united altogether to assure that circular economy is being implemented at every stage of lifecycle.

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Investigating Urban Resilience Through a Resource-Based View Framework: Evidence from an Empirical Survey

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Abstract. Urban Resilience refers to the ability of a city to absorb, adapt and transform in the face of a disturbance. Such a concept is increasing in importance as the continuous growth of cities leads them to face new uncertainties, challenges and often significant disruptions. Most extant literature focuses on the development of frameworks and indices that measure urban resilience. However, due to the inherent complexity of the concept as well as to the variety of research perspectives, the existence of several frameworks is quite confusing. Also, such frameworks fail to reveal how different urban factors affect resilience and the way it acts on the urban scale. The study aims to contribute to address such limits by investigating the main urban characteristics affecting resilience. Using a Resource-based view (RBV) perspective, the research develops a theoretical framework which links resources of urban systems (economic, social and environmental), urban abilities (leadership and governance, preparedness, cooperation and infrastructures and resources), and resilience capacities (absorptive, adaptive and transformative). The theoretical framework is then empirically tested through an online survey sent to a sample of urban stakeholders, namely, policy makers, emergency services, public organizations, academics, experts, infrastructure employees, public and private associations and organizations. The empirical analysis provides scholars with knowledge on the main factors that affect resilience and enables policy makers to better understand the way urban resilience arises based on the interrelationship between urban resources and capabilities.

Keywords: Urban Resilience · Resource-based view · empirical investigation

1 Introduction

Growing urbanization, climate change consequences and the recent Covid-19 pandemic have highlighted the vulnerabilities of cities across their economic, social and environmental systems [1–3]. In this context, Urban Resilience, defined as the ability of a city

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to absorb, adapt and transform in face of disruptions [4], emerges as a possible solution to minimize its vulnerabilities. Assessing urban resilience in the face of these events has gained importance among urban planners, policymakers, experts and researchers engaged in the urban planning and resilient initiatives [1, 5, 6]. In fact, scientific literature reveals that enhancing urban resilience allows cities to improve their performance and to better face the challenges the cities encounter. Being a city a complex system where many sub-systems are connected together, acting on urban resilience needs cities establish a resilience plan that encompasses the measurement and analysis of resilience across their economic, social and environmental systems [7]. In literature several frameworks exist and contribute to building city resilience plan, but they still present different limitations [8].

Due to the inherent complexity of the city and the concept of resilience itself, as well as to the variety of research perspectives, the current theoretical frameworks and indices are quite confusing and fail to reveal how different urban factors influence resilience and the way it acts on the urban scale [7, 9]. [6] and [10] also highlight that present frameworks underestimate the importance of including the perspectives of urban stakeholders who contribute to a more conscious city resilience building process. Recognizing these existing gaps, we propose a comprehensive framework designed to overcome these limitations by examining the extent to which urban factors influence resilience, incorporating perspectives from various urban stakeholders.

The framework proposed is based on resource-based view perspective (RBV). This theory originates within organizations and has been further expanded into different contexts, including the urban one in which it is possible to think about the city as a collection of both tangible and intangible resources and capabilities which can significantly impact the resilience [11]. The RBV perspective represents a valuable lens through which to analyze the complex interactions occurring in urban system, offering insights into how cities can enhance their strength various challenges.

2 Literature Review

The concept of resilience is characterized by the absence of a single definition [13]. Three main perspectives have been developed on this concept: engineering, ecological and socioecological. From the engineering perspective, systems have a single state of equilibrium and resilience is considered as the ability to absorb change to return to the previous state of equilibrium; from the ecological perspective, systems have multiple states of equilibrium and resilience is seen as the ability to adapt [2] and reach one of the equilibrium states after the interruption occurs [14]; finally, from the third perspective, the systems do not have any equilibrium states, but are seen as constantly changing [12] and resilience is seen as the ability to transform to respond to disruption [2].

According to these three perspectives, [15] proposed an analytical framework that breaks down resilience into three capacities that must be considered jointly. Absorptive capacity is implemented when the event has a low intensity, adaptation capacity refers to the changes made with the aim of persisting or resuming functioning after the interruption occurs [15, 16] and the transformation capacity is introduced when the required change exceeds the system's ability to adapt [15].

Several frameworks have been developed to build the city resilience. For example, the Hyogo Framework provides guidance on reducing disaster risk at the country level [8]. The Sendai Framework highlights the importance of governments and communities in reducing vulnerabilities and enhancing community resilience [13]. The City Resilience Framework, developed by Arup and the Rockefeller Foundation, provides cities with a tool for assessing their resilience level, understanding contributing factors, identifying critical areas and determining actions to enhance resilience [13].

While these frameworks advance knowledge and awareness about urban resilience by outlining key features and areas of actions that cities can use in the form of checklists [13], they fail in providing instructions and guidelines about urban characteristics essential to build resilience. Furthermore, many scholars emphasize the importance of promoting the participation of multiple stakeholders in the city's resilience-building process. In fact, the need to involve the community, policy makers, professional groups, local experts and stakeholders such as local businesses and civil society groups in the assessment of resilience has often been highlighted in the literature [6, 7, 10]. Based on the above considerations, significant gap exists in bridging the transition from theory to practice by trying to understand how resilience concepts can be truly implemented in cities [2] and what urban systems should do to move from a vulnerable to a resilient state [17].

3 Theoretical Background and Hypothesis Development

According to the RBV perspective, we identified the city's resources that are subdivided in three systems: economic, social and environmental. [18] and [19] highlight the role of urban systems and their resources in dealing with shocks, proving their significant impact on the three resilience capacities.

H1: The economic system positively influences urban resilience, i.e. absorptive capacity (H1a), adaptive capacity (H1b) and transformative capacity (H1c).
H2: The social system positively influences urban resilience, i.e. absorptive capacity (H2a), adaptive capacity (H2b) and transformative capacity (H2c).
H3: The environmental system positively influences urban resilience, i.e. absorptive capacity (H3a), adaptive capacity (H3b) and transformative capacity (H3c).

Various evidence supports the fact that urban abilities influence resilience capacities, and this is consistent with the RBV perspective adopted. [13] building upon the Resilient Maturity Model delineate urban abilities to enhance urban resilience. Governance plays a central role in defining strategies to enhance city resilience [20, 21]. [22] support that the notion of resilience is intricately connected to both strategic preparedness planning and proactive measures to mitigate disturbances as they arise. [23] sustain that infrastructures play a vital role in maintaining the quality of critical services during shocks, simultaneously enhancing adaptive capacity to respond to disruptions [24]. [25] underscore the importance of adopting a comprehensive and collaborative approach to fortifying resilience.

H4: Leadership & Governance positively influences urban resilience, i.e. absorptive capacity (H4a), adaptive capacity (H4b) and transformative capacity (H4c).

H5: Preparedness positively influences urban resilience, i.e. absorptive capacity (H5a), adaptive capacity (H5b) and transformative capacity (H5c).
H6: Cooperation positively influences urban resilience, i.e. absorptive capacity (H6a), adaptive capacity (H6b) and transformative capacity (H6c).
H7: Infrastructure & Resources positively influences urban resilience, i.e. absorptive capacity (H7a), adaptive capacity (H7b) and transformative capacity (H7c).

In the literature different studies highlight the connections between urban system resources and its abilities. In particular, the cases of [23] and [24] highlight how critical infrastructures foster the development of partnerships and preparedness plans to increase their overall efficiency. The relationship between systems and these two urban abilities is also highlighted by [26] which explores the relationship between the healthcare system and preparedness, cooperation and leadership & governance. Furthermore, in the research works the relationship between the economic system and infrastructure emerges [27], while [28] highlight how the economic system requires government policies for its development.

H8: The economic system positively influences urban abilities, i.e. Leadership & Governance (H9a), Preparedness (H9b), Cooperation (H9c), Infrastructure & Resources (H9d).
H9: The environmental system positively influences urban abilities, i.e. Leadership & Governance (H9a), Preparedness (H9b), Cooperation (H9c), Infrastructure & Resources (H9d).
H10: The social system positively influences urban abilities, i.e. Leadership & Governance (H10a), Preparedness (H10b), Cooperation (H10c), Infrastructure & Resources (H10d).

Through hypotheses H4, H5, H6, H7, H8, H9, H10, we propose that economic, environmental and social system might indirectly affect absorptive, adaptive and transformative capacity through urban abilities, namely Leadership & Governance, Preparedness, Cooperation and Infrastructure & Resources. The indirect effect of urban systems on resilience capacities can be understood based on the RBV perspective. In this perspective, abilities enable the utilization of resources [29]. Hence, we suggest that economic, environmental and social systems might positively and indirectly affect resilience capacities through urban abilities. We suggest the following hypotheses:

HM1: The urban systems resources might positively and indirectly affect resilience capacities through Leadership & Governance
HM2: The urban systems resources might positively and indirectly affect resilience capacities through Preparedness
HM3: The urban systems resources might positively and indirectly affect resilience capacities through Cooperation
HM4: The urban systems resources might positively and indirectly affect resilience capacities through Infrastructure & Resources

The conceptual framework is shown in Fig. 1.

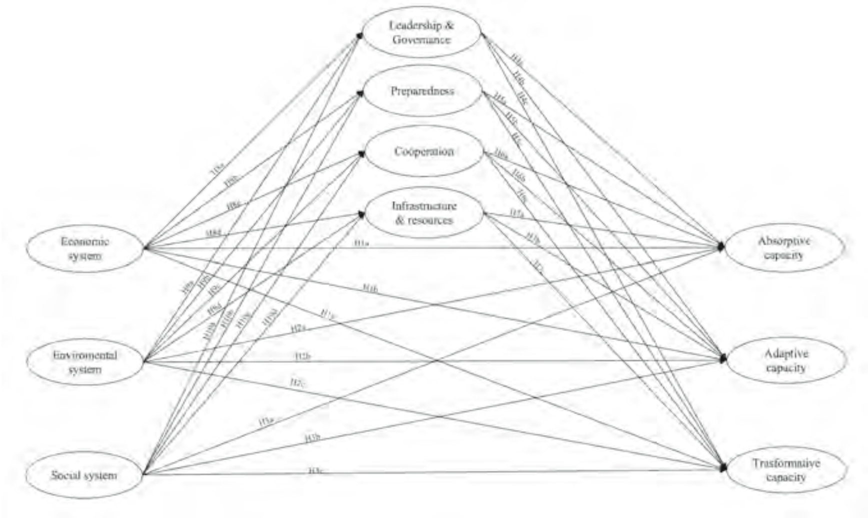

Fig. 1. Conceptual Framework

4 Research Method

Data was gathered through an online survey conducted among policymakers, experts and academics.

Prior to distribution, the survey was first reviewed during a meeting with academics and then was sent to a small sample of scholars and experts. The collected feedback has been evaluated and integrated in the questionnaire. The final version of the survey consists of four sections, in which all questions, except those related to demographic information about respondents, are measured with a 5-point Likert scale.

In the data cleaning phase five questionnaires were discarded due to incompleteness and inconsistency of the answers, reaching a total of 190 questionnaires considered acceptable.

"A priori" and "Post-hoc" power analysis were conducted, the number of collected questionnaires revealed a statistical power of 0.92. Through subsequent analysis no problems of non-response and common method bias were found.

We tested the model through PLS-SEM methodology because it is considered suitable for the analysis of complex models [30] which have an exploratory nature [31], does not require a normal distribution of the data and yields improved outcomes when working with significantly smaller sample sizes [32].

5 Results

The implementation of the (PLS-SEM) methodology comprises two steps: the assessment of the validity of the measurement and the structural model.

5.1 Assessment Measurement Model

The first step in the assessment of the measurement model is the evaluation of the factor loadings, since their values varying in a range from 0.605 to 0.949 are all considered acceptable. Regarding the descriptive statistics of the measurement model to assess the internal consistency reliability and convergent validity, we tested composite reliability (CR) Cronbach's alpha coefficient (CCA), and evaluated the average variance extracted (AVE).

For all constructs of the model the CCA values exceed the minimum value of 0.6, the CR values exceed the minimum of 0.7, and the AVE values are greater than 0.5 [33], hence we can conclude that the model has good internal consistency reliability.

Discriminant validity was assessed through [34] criterion. The findings show that this criterion is met for all the constructs of the model, as the shared variance for all model constructs does not exceed their respective Average Variance Extracted (AVE) values.

5.2 Assessment Structural Model

The second step is the evaluation of the structural model. First a variance inflation factor (VIF) is checked, since VIF values don't exceed the threshold of 5 [32], collinearity issues are not a problem in this study.

To check the model's quality, it is necessary to assess R^2 and path significance values. Results show that R^2 values vary in the range 0.481–0.756. Given that ranges of 0.25–0.5 and 0.5–0.75 represent weak and moderate explanatory power respectively, we can state that only preparedness presents weak explanatory power.

The assessment of the magnitude and statistical significance of the path coefficients was conducted and results are shown in Table 1.

Table 1. Path coefficients.

Hyp	Results	Hyp	Results	Hyp	Results	Hyp	Results
H1a	Rejected	H3c	Rejected	H6b	Supported	H8d	Supported
H1b	Rejected	H4a	Rejected	H6c	Rejected	H9a	Supported
H1c	Rejected	H4b	Rejected	H7a	Supported	H9b	Supported
H2a	Rejected	H4c	Rejected	H7b	Supported	H9c	Supported
H2b	Rejected	H5a	Supported	H7c	Supported	H9d	Supported
H2c	Rejected	H5b	Supported	H8a	Supported	H10a	Supported
H3a	Rejected	H5c	Supported	H8b	Supported	H10b	Supported
H3b	Rejected	H6a	Rejected	H8c	Supported	H10c	Supported

To test the mediating hypothesis about the role played by the four abilities of the urban system in the relationship between urban systems and resilience capacities, we evaluated the statistical significance of both the direct and indirect effects.

Following the indications of [35] we investigated on the type of mediation and the results obtained are presented in the following Table 2.

Table 2. Analysis of the mediation type

Independent variable (I)	Dependent variable (D)	Mediating variable (M)			
System	Capacity	HM1 Leadership & Governance	HM2 Preparedness	HM3 Cooperation	HM4 Infrastructure & Resources
Economic	Absorptive	No effect	Full mediation	No effect	Full mediation
	Adaptive	No effect	Full mediation	Full mediation	Full mediation
	Transformative	No effect	Full mediation	No effect	Full mediation
Environmental	Absorptive	No effect	Full mediation	No effect	Full mediation
	Adaptive	No effect	No effect	Full mediation	Full mediation
	Transformative	No effect	Full mediation	No effect	Full mediation
Social	Absorptive	No effect	Full mediation	No effect	Full mediation
	Adaptive	No effect	Full mediation	Full mediation	Full mediation
	Transformative	No effect	Full mediation	No effect	Full mediation

6 Discussion

Using a RBV perspective, it is possible to identify which factors allow to improve the urban resilience. The model is built considering the resources distributed in the three systems: environmental, social and economic and the four urban abilities, through which resources impact differently on resilience capacities (absorption, adaptation and transformation) and therefore on urban performance.

Since the direct effect of urban systems on resilience capacities is not statistically significant, as illustrated in Table 1, we can state that urban systems do not seem to directly influence resilience, this allows us to deduce that even highly performing urban systems alone cannot improve resilience directly.

The direct effect of the three urban systems on the four urban abilities, in contrast, is found to be statistically significant. This allows us to say that investments made to enhance the three urban systems, also have positive effects on the four urban abilities.

As shown in Table 1, the resilience of cities is not influenced by all urban abilities directly: investments in Preparedness and Infrastructure & Resources, would improve all resilience capacities; investments in Cooperation would only improve the Adaptive Capacity. In contrast, it appears that investments in Leadership & Governance do not have direct effects on resilience performance.

As can be seen in Table 2, two types of mediation emerged: no effect and full mediation. When mediation is full, the urban ability is necessary to allow the urban system to influence resilience. Hence, we can say that it is important to invest in urban abilities so that the resources of the urban system can influence resilience.

From the results on the type of mediation we can state that Leadership & Governance does not play any mediating role in the relationship between the three urban systems and the three resilience capacities. While Preparedness e Infrastructure & Resources play a full mediating role in the relationship between the three urban systems and the three resilience capacities. Therefore, it is important to invest in the development of elements that help increase these two abilities.

The development of early warning, emergency response and disaster management systems, as well as communication actions allow to increase the Preparedness ability. While investments intended for IT infrastructure and their security, critical infrastructures and their maintenance and continuity, and for compliance with standards help improve the Infrastructure & Resource ability.

In accordance with what emerges from Table 2, Cooperation plays a mediating role in the relationship between the three urban systems and adaptive capacity. Therefore, urban systems should invest in the development of partnerships with urban stakeholders and commit to building a cohesive and supportive community that encourages the active participation of citizens, to improve cooperation ability and, consequently, increase the influence of urban resources on the adaptive capacity.

The results obtained support the choice to implement the model through an RBV perspective as they highlight that urban resources can have an impact on resilience only through urban abilities, and a different level of development of these abilities translates into different performance in responding to disruptions, in accordance with what emerges from the definition of RBV itself.

7 Conclusions

Cities are facing numerous challenges, which will increase over decades and further try out urban communities. These issues underlined the importance of preparing contingency plans to respond promptly to disruptions and cope with a rapid reorganization of resources. In this scenario, the literature has highlighted how urban resilience has a central role in the decision-making process and in the formulation of response strategies. Existing frameworks offer qualitative insights but often lack a comprehensive consideration of all urban stakeholders. Consequently, we propose a model with the objective of identifying the primary factors within the urban system and assessing their impact on resilience through a resource-based view. The model explores the connections between resources, abilities, and the capacity for urban resilience, providing valuable managerial insights.

7.1 Policy Implications

The provided theoretical framework holds significant potential as a valuable asset in the field of urban planning. [36] asserts the critical role of urban resilience in the formulation of urban policies, emphasizing its contribution to the development of a resilient city capable of responding promptly to shocks. The presented model facilitates the identification of areas for improvement within the urban system, thereby ensuring a more robust formulation of strategies and optimal allocation of investments by political decision-makers.

7.2 Limitation and Further Research Directions

Study is not without limitations. First, the conceptual model considers a specific subset of resources and abilities, overlooking the extensive array of resources and abilities inherent in a city. Second, the response rate could be enhanced to ensure a larger amount of data to analyze and increase validity of the results. Third, for further insights, it would be beneficial to explore and employ alternative methodologies to validate the obtained results. Lastly, cross case analysis on different countries could be done in order to increase the generalizability of findings.

The results open new research possibilities, prompting a comprehensive exploration of the model's mediators to better understand their role in urban systems' resilience capacities. Such an investigation intends to furnish political decision-makers with precise insights, empowering them to steer policies and investments more effectively.

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Stakeholders' Engagement in CE Approach on the Built Environment, Albania Case

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Abstract. Circular economy principles remain relatively new tendencies in Albanian economy sectors, with some attempts throughout recent years, and until now, little research has been done in this aspect, especially in the construction sector. As the construction sector is connected with other sectors of the economy, its development or slowdown affects the indicators of other sectors. Moreover, this sector possesses numerous challenges, as special attention is needed on the impact that the momentum of construction and the expansion of the real estate market can have on the stability of the financial sector. Integrating the circular economy into the construction sector means understanding the role of stakeholders, their interactions, and the influences they can exert on the process itself, by adding value in each step of this chain process. By categorizing different groups of stakeholders and analyzing their activity regarding the circular economy approach in the construction sector in Albania, this paper presents a clear overview of what has been done until now, the consequences and benefits of these attempts, and also what can be improved in the future. The stakeholders' theoretical analysis has shown that the relation between different stakeholders presents difficulties in cooperation, although these groups aim towards mutual objectives and goals. In this context, Albanian economy presents difficulties, as this approach is widely influenced not only by political decisions, but also by cultural and financial matters, making it more challenging to make progress.

Keywords: stakeholders · construction · circularity economy · sustainability · policies · environment

1 Introduction

Circular economy (CE) is a system where materials never become waste and nature is regenerated [1]. Furthermore, circular economy can be defined as a system operating at micro-meso-macro levels, focusing on the 4R of reducing, reusing, recycling, and recovering materials in production consumption activities, aiming to achieve sustainable development, enabled by business model innovation and responsible consumers, and supported by the quadruple helix collaboration [2]. In this context, CE has its fundaments in sustainability effectiveness and long-life products by creating a closed loop, while linear economy is based on the concept take-use-dispose. The circular approach changes the way in which value is created and preserved, how production is made more sustainable

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and which business models are used. Another difference on these two types of economy is sustainability. Within a linear economy, the focus is on eco-efficiency, which means trying to minimize the ecological impact to get the same output [3]. Within a circular economy, sustainability is sought in increasing the eco-effectiveness of the system, where not only the ecological impact is minimized, but that the ecological, economic, and social impact is even positive [4].

The transition from linear economy towards circular economy possess numerous challenges starting from the possible lack of information that the involved parties may have, up to technological costs needed for circular approach implementing. In Albania, methods of recycling and reusing products or certain inputs were present since the '60s [5]. After the '80s, the first circular approach attempts were seen because of the economic difficulties that the country was experiencing. When researching the related literature, it is concluded that the circular approach is used on some specific businesses/sectors such as recycling, waste management, olive oil producing, etc. [5].

Special focus has been given to environmental protection nowadays, due to the inherited problems with environmental pollution. Being part of the European Union (EU) is an early aspiration of Albania, starting from Thessaloniki European Council summit in June 2003, when Albania, together with other Western Balkan countries, was identified as a potential candidate for EU membership. Since then, numerous and continuous attempts have been made to achieve the requirements for improvement grouped in six clusters by the European Commission. Each negotiation cluster contains different policy fields called chapters. Cluster 4 "The Green Agenda and Sustainable Connectivity" covers transport (Chapter 14); energy (Chapter 15); trans-European networks (Chapter 21); and environment and climate change (Chapter 27). While Albania has made some progress in the areas of transport and energy, limited progress was made in the areas of environment and climate change [6].

Construction is an industry that contributes negatively to the environment and ecosystem as according to previous studies construction and demolition waste accounts for 30% of total waste produced globally [7] with an estimated average of more than 35% of all construction and demolition waste disposed in landfills annually [8]. During 2022, Albania shifted gradually away from agriculture towards construction, manufacturing and services. In 2022, the construction sector's share in gross value added increased to 11.2% in 2022, approximately 1 pp higher than its average in 2015–2019 [6]. In this context, the construction industry is contributing towards the economic growth of Albania as one of the most influencing sectors, even though the population is shrinking according to the data of Institute of Statistics [9].

As in every other industry, different groups show interest on the construction industry, its development and its impact. These groups, defined as stakeholders, are affected or can affect the achievement of construction businesses' objectives [10]. Regarding the construction industry importance in the Albanian economy, and on environment and pollution, this paper gives an overview of different groups of stakeholders and their activity by presenting what has been done until now, the consequences and benefits of these attempts, and also what can be improved in the future.

2 Literature Review

A review of the existing foreign and Albanian literature has revealed that most publications related to CE in the built environment together with its components are from European and Asian countries [11, 12], and to the best of the authors' knowledge, no studies are concerned to the state of practice of circular construction in the built environment in Albania. Thus, this study will provide new information regarding stakeholders and circular approach on the construction industry in Albania.

A detailed overview of previous studies has revealed that research interest in stakeholder management has turned to the descriptive approach. Through a critical qualitative review of stakeholder management process defined in the existing literature, three main problems of previous studies are identified: very few methods and tools are available to identify all stakeholders and their interests; limited studies involve the change management about the stakeholders' influence and relationship; and few studies are capable of reflecting the influence of the entire relationship network in practice [13].

Previous studies group stakeholders in different categories: internal - which directly influence the project, and external stakeholders - which indirectly influence the project [14]; primary stakeholders – which interact on daily basis over major activities, and secondary stakeholders – which interact with the project unexpectedly depending on the project's stage [15]; according to their engagement: senior management, project core team and project recipient stakeholder groups [16]. The project's dependence on internal or external stakeholder need not be ignored, as project manager, client and consultants were found to have maximum influence on project spheres [15]. Therefore, they can be grouped during strategic planning early on Project Life Cycle.

Moreover, during the qualitative review of existing literature, was observed that Project Management Consultancy is identified as the key stakeholder which makes the project successfully completed [14]. An empirical study conducted that if other stakeholders are managed adequately, the quality of the project improves, costs can be controlled and the timeline factor can be assessed and improved, leading to a successful completion of the construction project [14].

Other studies demonstrate that the application of circular strategies is dependent on external factors, collaboration, and synergy between stakeholders [17, 18], while the collaboration throughout the whole value chain process is essential for developing a fully circular built environment [19]. To drive towards sustainable development, implementing circular principles in construction projects by connecting stakeholders has become a priority [20]. As per above, the existing literature concludes that stakeholders play an important role on the construction sector, especially in construction projects, whilst their impact is meaningful for these projects.

3 Methodology

In this paper, primary data was gathered using face to face interviews conducted with different groups of stakeholders of the construction industry. A total of 40 internal and external stakeholders were contacted, while 30 interviews were conducted. The interviews consisted in four main parts: introduction with the interviewed stakeholder in order to know them better; questions regarding the best practices known by them on the circular approach in the construction industry; questions regarding present challenges in terms of better cooperation between stakeholders; and open discussion on any key point that the interviewed stakeholder may want to highlight.

Moreover, strategic documents and policies, along with previous studies in this field, were analyzed, as second data. In this context, the theoretical qualitative analysis of interview responses gathered and also the reviewed literature and strategic documents, have served as basis of concluding in the last section of this paper.

4 Results and Discussion

4.1 Inherited Problems of Construction Sector in Albania Related to the Circular Approach

Albania has a long history of land ownership problems, carried over from the transition period after the fall of communism in the '90s [21]. This transitional period has resulted in uncontrolled constructing, where buildings were constructed without legal permission [22] and potentially not complying with any criteria or requirement for constructing. Consequently, these buildings do not possess circular qualities, making it much more difficult to adapt them in the circular approach, and also on the other hand it increases the number of non-circular buildings in Albania. Such an uncontrolled growth of these building premises has also induced a large number of legalizations requests, with an impact on today and the near future referring to the long process of legalization. Albanian institutions do not possess any data regarding the number of these buildings that have been constructed without legal permission, but only the number of legalizations permits, which makes it difficult to assess their impact on the circularity approach that has been absent during the construction.

According to the data of State Cadaster Agency [22], as described in Fig. 1, the number of legalization permits had its peak on 2016. The significant decrease in the number of legalizations in 2019 was a consequence of the approval in January 2019 of a change in the Law on local taxes, which conditioned legalization on the prior payment of the infrastructure impact tax [22]. This was corrected only in August 2020 and immediately had the effect of almost doubling the number of legalizations.

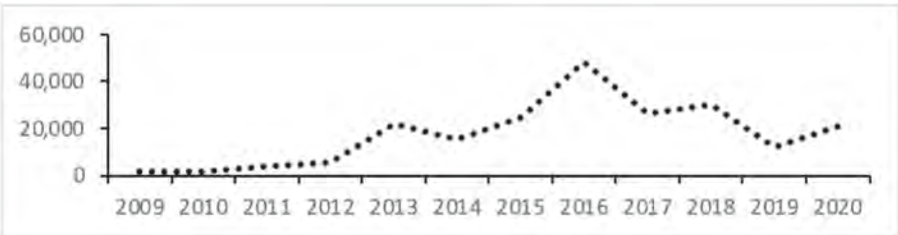

Fig. 1. Legalizations permits in Albania 2009–2020 [22].

Another impact on the construction sector and not only, was that of the catastrophic earthquake that Albania experienced on November 26th, 2019, resulting in human fatalities and collateral damage of building residences. In order to recover, Albanian Government drafted different decrees and action plans to help the communities that were most affected [23]. Partners, civil society organizations, and donators contributed financially to provide help. At the International Donors' Conference, the EU pledged €115 million from its budget to rapidly reconstruct and rehabilitate key public buildings [24]. The program EU4Schools came to life with a budget of EUR 75 million from the EU and United Nations Development Program (UNDP) own contribution of EUR 765,000 to target 63 educational facilities in the 11 affected municipalities [24]. While conducting the program, two key principles were taken in consideration: #BuildBackBetter and #BuildBackTogether, implying sustainable stronger structures bearing the highest international standards of quality and safety, with renewable energy sources, and fully accessible. This sustainable and circular approach until now is finalized in 34 education institutions [24].

Although these projects had a circular and sustainable approach during rebuilding and reconstruction, many buildings were renovated by citizens themselves and thus not offering certainty on the sustainable approach. According to the Durrës Municipality [25], for over 80% of the damaged apartments that were evaluated for a DS1-DS3 damage level (from light to medium-severe damage) [26] the repair was done by the residents themselves and was not certified by any institution. Furthermore, in these conditions, a financial evaluation of the repairs made by the residents is impossible to be carried out.

4.2 Stakeholders in the Construction Sector in Albania and Their Engagement Regarding CE Approach

According to the reviewed literature, different categorizations of stakeholders are known [14–16]. In order to analyze better the impact of different stakeholders in the circular approach on the construction industry in Albania, throughout this paper, stakeholders are grouped as internal and external stakeholders. Internal stakeholders are made of individuals who are team associates of the construction project or are supplying with funds; whilst external stakeholders are individuals who were directly impacted or influenced from the project, but are not directly concerned in construction businesses [27]. In these terms internal stakeholders can be: construction business employees, project management team, contractors/subcontractors, suppliers, project owners, costumers, banks; and external stakeholders can be: government, media, civil society organizations (CSOs) general public, environmentalists, social services, political organizations, and every interest group that believes it has a stake on the project.

Apart from analyzing certain policies and documents regarding these stakeholders' involvement in CE methods in built environment in Albania, interviews were made with groups of stakeholders that authors considered to be more representative and impactful on construction industry, based on the literature review and the actual economical reality in Albania, such as: construction businesses owners, costumers and bank managers (as internal stakeholders), and governmental employees, environmentalists and researchers (as external stakeholders).

From the interviews conducted, a qualitative analysis was done for both internal and external stakeholders. As provided from these groups' answers, CE approach in the construction industry in Albania is a rather new approach, quite challenging and innovative. During recent years, in internal stakeholders, different levels of engagement and involvement is seen regarding these practices. When referring to banking system – as an important factor in the economy because of its traditional functions– according to our interviews and certain policy documents, it is concluded that especially the largest banks have undertaken policies oriented towards sustainability and Sustainable Development Goals accomplishment which need to be highlighted as new tendencies [28, 29].

Banks in Albania are now offering also supportive services regarding circular approach in the construction sector. Moreover they offer environmental, social, and governance (ESG) housing loans for living premises equipped with energy efficiency certificate and business loans from the European Bank for Reconstruction and Development, combined with a 15% grant financed by the Instrument for Pre–accession Assistance (IPA) funds of the EU, while also offering technical assistance that enables Small and Medium-sized Enterprises (SMEs) to optimize their investment needs to achieve compliance with EU Priority Directives. Also financing and supporting agreements between investors and companies that are increasingly taking ESG into account by financing the production of solar panels with a payback period of up to 5 years in Euro and 7 years in Albanian Lek [28] are offered. Banks have drafted action plans, policies, public commitments, and company goals on environmental protection by offering green loans which are energy efficiency loans for individuals that want to use the loan for improvements that will lead to energy savings and CO_2 emission reduction for their living premises. A new project is being implemented by National Commercial Bank in its headquarters consisting in solar power and energy saving [29], being a major step in investing towards circular buildings from the banking sector.

On the other hand, other internal stakeholders as construction businesses, have made steps forward in using CE principles in their projects. From the interviews is concluded that the largest construction companies such as "Kontakt", "Balfin Group", "Orion Construction", which have a big share of the Albanian market are orienting their projects towards circularity in terms of maximizing green spaces and protecting the environment during constructions by using ecological materials and reducing inert waste. Also, they offer residency buildings with solar energy panels, so residents can use renewable energy and be more efficient on energy usage. Furthermore, the adoption of ISO standards in the design and implementation of construction projects is another way of contributing towards circular buildings. If the construction businesses handle properly the whole process of integrating circular principles in their projects, added value can be created on each of the project phases.

Costumers, another group of stakeholder interviewed, claim to be more oriented towards circular buildings rather than old and traditional buildings, as they assess that is more convenient and efficient in terms of well-being, comfort and monthly expenses for energy and water consumption. Although, costumers claim in general to be less informed on the circular design of buildings as this information is not gathered and published; orienting the whole system towards the need of raising awareness on CE principles and their implementation. Costumers, which are ready to buy these innovative residences, are supported by green loans that different banks in Albania offer nowadays. The cooperation between these costumers and banks results in a positive output of the buying process, and also positively influences all involved parties: banks, costumers, construction businesses, and other influenced parties.

As per the external stakeholders, from the interviews conducted with governmental employees combined with revision of policies and strategic documents, a new era of adopting circular principles is distinguished. Strategic policy documents such as National Strategy for European Development and Integration 2030 [30], which is the main strategic document that gives directions and priorities for the development of economic and social stability of the country on the path of its integration into the European Union, including the interconnection with the 2030 Agenda [31]. The three main pillars of this strategic policy document are: Democracy and strengthening of institutions and good governance, Agenda for sustainable economic development, green approach, as well as social cohesion. Also, referring to the improvement of the legislation, the main planning document in the field of municipal, non-municipal and hazardous waste management in Albania has been approved and covers the time period 2020–2035, namely the Strategic Policy Document and the National Sectoral Waste Management Plan [32]. This document refers to the concept of “zero waste” as a method of using the principles of the circular economy in relation to the generated waste. The National Energy Strategy for Albania 2018–2030 [33] is an essential strategic document for the national energy sector, in coherence with the objectives of the European Green Deal [34] such as construction and renovation, accelerating the transition to sustainable and intelligent mobility, and eliminating pollution. As mentioned, no document regarding specifically circular approach in the construction sector has been drafted, concluding in a gap of governmental incentives offered for the construction businesses and other parties, taking into consideration that efforts of the construction businesses are interconnected with the support offered by government.

Environmentalists and researchers appear to be oriented towards spreading the information of circular principles and their proper use, by using certain campaigns and studies [2, 5] to raise awareness even though their tentative remains not widely noticed. More media coverage is needed in this context, in order to spread the information. As external stakeholders, environmentalists and researchers appear to be quite involved in the environmental impact of new constructions in Albania. Once again, the lack of communication channels affects their contribution towards a more circular economy in the built environment.

5 Conclusions

As construction sector is related to other economy sectors, any changes in the economy may affect also other sectors, including the construction sector, and vice versa. In this context, having a circular construction sector would contribute for the better to the whole economy of the country. Integrating the circular economy into the construction sector means understanding the role of stakeholders, their interactions, and the influence they can exert on the process itself, by adding value in each step of this chain process.

In Albania, the relation between different stakeholders regarding CE presents difficulties in cooperation, although these groups aim towards mutual objectives and goals and operate within the same environment. As such their efforts are intertwined with each other, resulting in the need of coordination. Unlike the banking systems which uses an internal system to communicate, such a way of communicating is not present in the construction industry. From the analysis of interviews' answers, it is concluded that communication between different stakeholders is not properly done due to improper channels and in the worst cases, the lack of them.

The efforts of different stakeholders have resulted in better legislative framework, new banking products and services, governmental support for waste management, more coverage by environmentalists and also new circular approach implemented by construction businesses. However, stakeholders' theoretical analysis has shown that the relation between different stakeholders presents difficulties in cooperation, although these groups aim towards mutual objectives and goals. In this context, Albanian economy presents difficulties as the circular approach is widely influenced not only by political decisions, but also by cultural and financial matters, making it more challenging to make progress.

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Circularity KPIs and Criteria for Material, Flow and Design Assessment

Development of Circularity Assessment Indices for Construction Sector: A Critical Review

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Abstract. The efficient assessment of circularity in buildings requires a comprehensive consideration of diverse elements such as material selection, design principles, construction methods, operational effectiveness, and end-of-life management. However, the absence of a consistent methodology poses a significant challenge in circularity assessment, as extant evaluation techniques either offer a broad perspective on circularity or concentrate on specific components. The lack of clarity in the variations and ranges of circularity indicators further hampers the ability to thoroughly evaluate a building's performance, leading to a preference for a qualitative approach. This study aims to overcome the challenges associated with the development of circularity assessment indices by proposing a generic framework for index generation, providing guidance to tool developers and decision-makers in understanding the rationale behind circularity indices within the building environment literature. To achieve this goal, the study conducts a literature review elucidating common methods employed in developing circularity indicators and indices as well as the aggregation methods encompassing both qualitative and quantitative indicators, emphasizing how their weights are determined and utilized in the aggregation process. This critical review offers insights into current practices, identifies challenges, and fosters a deeper understanding of the inherent complexities in circularity assessment. Ultimately, this study contributes to the advancement of methodologies for evaluating and enhancing circularity in building, addressing a vital aspect of sustainable construction practices.

Keywords: Circularity Assessment · Circularity Indicators · Circularity Index Generation · Construction Sector

1 Introduction

The imperative for stakeholders to deliberate on strategies for ensuring their buildings cater to their requirements while aligning with sustainable and environmentally friendly concepts-such as green building, zero energy, carbon neutrality, and the circular economy (CE)-is steadily increasing. The CE represents an economic model that aims to eliminate

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waste production and foster the perpetual use of resources by creating closed-loop systems. Within the building sector, employing CE principles is at the top of environmental and sustainable development agendas, given the sector's high footprint and elevated consumption of resources. CE principles can be seamlessly applied throughout all life cycle stages, particularly in building design, construction, operation, and end-of-life management, to minimize waste, reduce carbon emissions, and enhance the circularity value of materials and products used. By embracing the tenets of the CE, the building sector emerges as a pivotal contributor to the realization of a more sustainable and resilient future.

To ensure that buildings in the construction industry align with CE concepts, it is imperative to employ robust criteria and indicators grounded in established standards [1], insight from stakeholders [2], and established practices [3]. This approach guarantees comprehensiveness and high-quality assessments. The criteria and requirements established by the CE should be translated into the use of various metrics or indicators to measure a building's performance and its impact on the environment and human health [1–3]. Through the application of such metrics and indicators, stakeholders can identify areas requiring improvement, maintain consistency and quality over time, and optimize their use of time and resources.

Several circularity tools, methods, frameworks, and indexing systems have been created based on such standards and metrics. Examples include the Whole-Building Circularity Indicator (WBCI) [1], the Building Circularity Indicator (BCI) and its derivatives [4], as well as HOUSEFUL's Building Circularity Methodology (BCM) [5]. These tools enable stakeholders to make well-informed decisions based on high-quality standards and predetermined criteria. Moreover, they provide opportunities to retain the value of projects and potentially elevate them to higher standards owing to their superior quality and services that support sustainability, ecology, and human health [3].

However, the assessment of circularity faces numerous challenges, with one significant issue being the establishment of transparent criteria for quality [1]. The lack of clearly defined and easily understandable criteria hampers the promotion of sustainable and environmentally friendly concepts within the building sector. Typically, current indices for building construction focus on specific goals or aspects of circularity, such as minimizing the use of new materials and closing the waste loop. However, focusing solely on individual aspects can impact other facets and, therefore, overall circularity levels, leading to incomplete and non-comprehensive results. Another obstacle is the varied understanding and appreciation of circularity strategies among stakeholders. End-users, for instance, may perceive the incorporation of recycled or secondary materials as a compromise in the building's quality. This underscores the necessity of considering additional criteria that can effectively communicate the added values and benefits of implementing CE practices to a wider range of stakeholders along the value chain. Another example of the challenges is that available tools, while effective in providing synthetic data for decision-making and production management, often fall short of facilitating meaningful communication of information to stakeholders. Karaca et al. argue that while measurable criteria are generally preferred in developing indices, the scoring may be criticized due to differences in stakeholder opinions. To address this, they recommend using different weights for various perspectives, allowing for a customized approach to criteria [2].

This research aims to critically address the abovementioned gaps by reviewing the processes and steps involved in developing circularity assessment indices for buildings. It presents a review of how common circularity indices are developed or generated. Additionally, it discusses their aggregation methods, considering both qualitative and quantitative indicators, focusing on how weights are identified and used in the aggregation process. Ultimately, the research aims to guide tool developers and decision-makers in the academic and sectoral areas by providing them with a step-by-step generic index generation framework.

2 Circularity Assessment Frameworks

Implementing CE in the construction sector poses a significant challenge, primarily due to the absence of standardized assessment indicators. This dearth hampers the ability to effectively measure the impact of CE initiatives and compare their success across relevant industries and regions. To address this challenge, it is necessary to consolidate the most common assessment criteria and indicators into a unified approach covering all CE requirements and ensuring transparency and comprehensiveness in addressing CE strategies and principles. Therefore, establishing frameworks with a consistent methodology is critical for assessing circularity within building processes.

In this section, two frameworks were selected based on their wide-ranging applicability in the field. The chosen frameworks underwent thorough analysis to gauge their effectiveness in assessing the circularity of building materials and construction processes. Each assessment framework provides a measurable methodology for evaluating the effectiveness of resource management, reuse, and recycling in the building sector.

The first example is the Circular Construction Evaluation Framework (CCEF) proposed by Dams et al. (2021) [6]. CCEF is a noteworthy example of circularity assessment as it is based on international design code guidelines and critical literature analysis to develop assessment considerations for the selection of circularity criteria. CCEF is a versatile framework applicable to both existing buildings and newly proposed projects and can be used by diverse stakeholders involved in project development. The methodological approach of CCEF involves quantifying the level of circularity within the examined project with respect to several relevant criteria. This assessment occurs at two distinct levels: the whole-building level and the building element level. Qualitative and quantitative evaluations are employed to score circularity credentials for criteria at each level. In a whole-building assessment, 14 criteria are employed and categorized into four groups: 1) recorded information design, data, and materials; 2) adaptability in design; 3) simplicity in design; and 4) health and safety. At the element level of assessment, 14 criteria are delineated and grouped under durability, material inventory, and finishes. Additionally, three individual criteria lack a higher categorization but are integral to the assessment: reversibility of connections, reusability percentage, and recyclability percentage. The structured organization of criteria into larger groups facilitates a comprehensive evaluation of circularity across different dimensions of construction projects.

The second framework, the Disassembly and Deconstruction Analytics System (D-DAS), is designed to seamlessly integrate end-of-life performance evaluation and consideration into the design stage and process of buildings to optimize their circularity [7]. The system's main goal revolves around selecting materials, relying on incorporating the principles of Design for Disassembly (DfD). This approach not only facilitates efficient material use and recovery but also significantly reduces waste in the built environment at the end of a building's lifecycle. Building information modeling (BIM) is used and expanded upon by D-DAS to develop a four-layer system architecture. These layers collaborate harmoniously to create a unified system. The data used in the calculations are drawn from building design (parametric building models, materials), building material specification (material properties and status), and deconstruction and demolition information (historical data). To execute its functionalities, the framework employs a Revit plug-in, enabling it to perform three essential operations to optimize and assess certain circular aspects of the project.

3 Circularity Indicators

Circularity is evaluated through a range of circularity indicators or a specific metric that uses single or aggregated scores [4]. Circularity metrics are commonly employed to measure the impacts or benefits generated by circularity strategies. In resource efficiency and sustainability performance (covering environmental, economic, and social aspects), there has been a proliferation of indices and frameworks, contributing to an excess of indicators [1]. In consideration of the aforementioned points regarding circularity metrics, this section refines its focus to analyse indicators related to both material and building circularity, emphasizing three key areas: (1) laying the groundwork for circularity metrics used thus far, (2) assessing the validity of current circularity metrics based on predefined requirements and a CE definition anchored in the sustainability concept, and (3) offering guidance and recommendations on how to generate circularity metrics.

Unlike most products in the manufacturing industry, buildings possess extended service lives, incorporate diverse materials, involve multiple stakeholders, and are highly customized and context-dependent. These distinctive characteristics make it challenging to implement standardized circularity indicators in the building sector [1]. Using reliable indicators becomes critical when assessing progress toward the CE. Given the fundamental purpose of a circularity indicator, which is to objectively assess critical aspects and dimensions of CE in construction and built environments, the majority of existing circularity indicators employ quantitative measures. However, indicators can be quantified or qualified based on observations, measurements, calculations, or a combination of complex methods. Focusing on these objectives sheds light on the specifics of the *Material Circularity Indicator (MCI)* and its adaptation to the building context, considering complementary design aspects to generate the *Building Circularity Indicator (BCI)* and its derivatives. Additionally, attention is given to *HOUSEFUL's Building Circularity Methodology (BCM)*. These selected indicators are evaluated below to provide a comprehensive methodology perspective for circularity assessment.

The Material Circularity Indicator (MCI), developed by the Ellen MacArthur Foundation in 2015, stands out as a sophisticated metric designed to gauge the circularity of industrial materials and products [8]. Unlike simpler indicators, the MCI provides a comprehensive evaluation of a product's circularity by emphasizing the maximization of material restoration within its components.

Comprising three key product characteristics, the MCI focuses on the amount of virgin raw materials (V) attributed to the product, the amount of unrecoverable waste (W) associated with the product, and the utility factor (X), which accounts for the product's lifetime. Calculation of the MCI involves considering the proportion of material input (virgin or non-virgin), material output (energy recovery or landfill disposal), and the technical lifecycle of a product. Together, these factors represent the theoretical circular capacity of each product. In the context of buildings, a Bill of Materials (BOM) is used to calculate the MCI for individual products.

What sets the MCI apart is its adoption of a multidimensional assessment methodology, taking into account various factors. Its primary input involves a thorough investigation into the proportion of resources sourced from both virgin and recycled materials, as well as components repurposed from previous usage. In addition, the MCI considers the utility gained from using the product by comparing the duration and intensity of product consumption to industry norms for similar product types. To calculate the MCI of a product, the Linear Flow Index (LFI) and the factor F(X) are employed. The factor F(X) is formulated as a function F of the utility X, determining how the utility of a product affects its MCI [8].

The MCI is used within the built environment context to formulate the Building Circularity Indicator (BCI) [4]. The BCI calculation adopts a bottom-up approach, employing a hierarchical methodology that diverges from relying on the calculation and aggregation scores of different criteria. Instead, it uses a progressive calculation involving four indicators. This process begins with the MCI and advances through the Product Circularity Indicator (PCI), followed by the System Circularity Indicator (SCI), culminating in the overall Building Circularity Indicator (BCI). The overarching concept of the BCI is to scrutinize input, usage, and output. The development methodology of the BCI complements the original MCI model for subsequent indicator calculations with design criteria rooted in an extensive list of KPIs. These KPIs are derived from expert semi-structured interviews, followed by the scholar's subjective prioritization to streamline the list. The result is a selection of the most crucial circularity indicators, subsequently validated by an expert panel. This comprehensive process yields a conceptual framework translated into an assessment methodology, which is then tested and validated through a case study using Excel functionality. The circularity indicators exclusively encompass technical requirements, comprising two components: (1) material specifications and (2) design for disassembly (functional, technical, and physical). Verberne's BCI marks the pioneering effort in establishing whole building circularity indicators, laying the foundation for subsequent BCIs and other building circularity models. These later models build upon the initial BCI, addressing some of its limitations.

The last examined indicator originates from the Horizon 2020 HOUSEFUL project (2018–2022), which specifically addresses "Innovative circular solutions and services for new business opportunities in the EU housing sector". The HOUSEFUL project introduces a global circularity indicator known as the Building Circularity Score (BCS) [6]. The novel indicator employs a methodology designed to evaluate circularity at the initial stages of housing design, encompassing new constructions and retrofits. The HOUSEFUL approach is fundamental in determining circularity levels, relying on six key pillars: energy, water, material balances, social and environmental impacts, and life cycle cost reduction. Operating under a life-cycle-based methodological approach, the BCS aligns with established building sustainability standards and practices, such as those endorsed by the CEN Technical Committee 350 (CEN TC 350) and the European Union (EU) LEVEL(s). Notably, the BCS offers the potential to enhance water and energy circularity across various life cycle stages.

4 Index Aggregation Techniques

In general, criteria and indicators play a critical role in indicating the direction of change over time and across various units. They also serve as valuable instruments for establishing policy priorities, benchmarking, and performance monitoring. When disparate indicators are amalgamated into a single index (referred to as a ranking, method, or tool) based on an underlying model, the resultant composite is termed an "index" or aggregated indicator [9]. While it is acknowledged that science cannot provide an entirely objective approach to creating a definitive index that encapsulates a complex system, it can significantly enhance the robustness and transparency of aggregation processes. Consequently, this section provides aggregators and tool developers with a generic index generation framework (Fig. 1) as a checklist for constructing an index, encompassing a generic framework for index generation steps and methodology. The index creation process begins with the establishment of a solid theoretical framework. The framework should explicitly identify the phenomenon under assessment, its constituent parts, distinct indicators, and weights reflecting the relative importance of these components and the dimensions in the final composite. Emphasis should be placed on measuring what is desirable rather than solely relying on readily available indicators.

Variables should be selected based on their applicability, analytical quality, timeliness, and accessibility. The potential hindrance of missing data to the development of reliable indices is acknowledged, and a well-managed step for the imputation of missing data should be incorporated in such situations. The uncertainty associated with imputed data must be considered when estimating variance.

An increasing number of decision-makers find themselves tasked with developing aggregated indicators in contemporary settings. Unfortunately, many of these indicators are often selected arbitrarily, lacking thoughtful consideration regarding their potential interactions with other indicators.

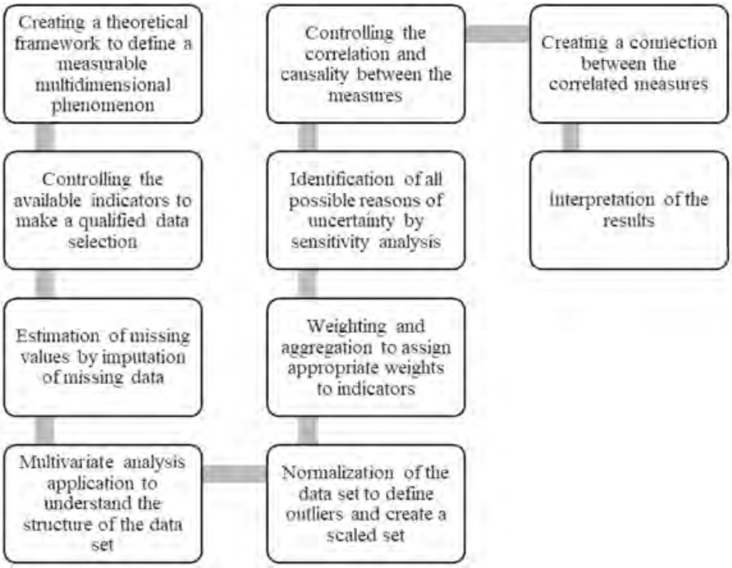

Fig. 1. A generic structure of index generation steps (Source: own elaboration).

Consequently, the applicability of the dataset can be effectively assessed through Multivariate Analysis (MVA), which not only facilitates comprehension of how methodological choices impact results but also serves as a valuable tool in this context. Among the prevalent MVA methods are Multiple Linear Regression Analysis, Principal Components and Factor Analysis, Cronbach Coefficient Alpha, and Cluster Analysis, as outlined in Table 1.

Before calculating an index, it is imperative to normalize the sub-indicators measured in different units, a crucial technique preceding any data aggregation. This "normalization" process is essential due to the common occurrence of diverse measurement units among indicators in a dataset. Furthermore, a challenging aspect involves determining appropriate weights [10]. This issue is closely tied to the implicit importance of attributes, as exemplified by the 'trade-off' between pairs of criteria during the aggregation process [11]. Consequently, this study delves into the literature with a particular emphasis on methods for generating indices, specifically focusing on weighting and aggregation. Table 2 outlines the commonly cited methods in this field, providing a comprehensive overview.

Table 1. A short table of Multivariate Analysis Methods (MVAs)

MVA Methods	Specifications	Mathematical Formulation	Explanations
Multiple Linear Regression	Handling a large number of variables of different types	$\hat{Y} = \alpha + b_1X_1 + \cdots + b_nX_n$	$\hat{Y}$ is an indicator $b_1 \ldots b_n$ are the regression coefficients (weights) $X_1, X_2, \ldots, X_n$ are sub-indicators
Principal Components and Factor Analysis	Assessing statistical characteristics in the data with a lack of correlation	$Z_j = \sum_{i=1}^{p} a_{ij}X_i$	$X_1, X_2, \ldots, X_p$ are variables $Z_1, Z_2, \ldots, Z_p$ are principal components
Cronbach Coefficient Alpha	Utilizing a coefficient of dependability which allows for assessing the strength of correlations between a group of sub-indicators	$\alpha = \frac{p.\bar{r}}{1+(p-1).\bar{r}}$	p is the number of indicators $\bar{r}$ is an average intercorrelation among the indicators
K-means Clustering Analysis	Providing an alternative method for classifying variables and shedding some light on the data set's structure	$J = \sum_{J=1}^{K} \sum_{n \in S_j} \lvert X_n - \mu_j \rvert^2$	n is the sample size k is number of clusters n is the examples to one of k clusters

Table 2. Weighting and Aggregation Methods Generating Indices

Normalisation Methods	Weighting Methods	Aggregation Methods
Ranking [9, 10]	Equal Weighting [11]	Compensatory Aggregation [8, 13, 14]
Distance to target [9, 10]	Budget Allocation Process [13]	Non-compensatory Aggregation [15–17]
Z-score [9, 10]	Analytic Hierarchy Process (AHP) [18]	Mazziotta–Pareto Index (MPI) [19]
Min-max [9, 10]	Conjoint Analysis (CA) [14, 20]	Penalty for a Bottleneck [21]
Proportionate [12, 22]	Correlation Analysis [14, 23]	Mean–Min Function [24]
	Multiple Linear Regression Analysis [25]	ZD Model [10]
	Principal Components and Factor Analysis [26, 27]	Directional Benefit-of-the-Doubt (BoD) [28]
	Data Envelopment Analysis (DEA) [29]	

5 Conclusion

A circular building aligns with the principles of the CE, emphasizing design, development, operation, and use in a manner that minimizes environmental impact and maximizes material circulation. The central objective within the construction sector is to diminish reliance on virgin materials, employing circular design strategies, efficient material characterization, and thoughtful material selection. Achieving this objective necessitates the adoption of a comprehensive circularity approach that facilitates the expression of 'circularity indicators' as quantifiable values. This approach is essential in reflecting the CE's core tenet of optimizing the retention of value in materials and resources. In this regard, the current paper contributes by outlining the rationale behind circularity frameworks and indicators. It accomplishes this through a comprehensive review of two prominent frameworks and various widely-used indices in the literature, all aimed at quantifying circularity in buildings. The analysis of these tools provides valuable insights, enabling the formulation of a generic index generation framework. This framework serves as a guide for tool developers and construction industry professionals, offering a systematic overview of the circularity index generation process. It lays the necessary steps and requirements involved in generating circularity indices for buildings. Additionally, the paper sheds light on prevalent aggregation methods for indicators, offering clarity on the generation of a unified index.

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An Analysis of the Circularity Indicators at the Building Design Level

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Abstract. The built environment is responsible for around 50% of the total extraction of raw materials and 25% of all waste in the European Union, which comprises numerous materials that still have the potential for reuse and recycling. Due to the planet's finite reserves, transitioning towards a circular approach in the built environment to achieve sustainability, particularly at the building design stage, is inevitable. At this level, the role of indicators as the primary measurement tools is essential to assess the circularity in the built environment and guide the implementation of circular economy (CE) principles into the design and construction of buildings and infrastructure. This study aims to analyse international and European policies and standards and extract and present the remarkable and relevant existing circularity indicators at the building design level. Subsequently, a categorised list of the most employed indicators to measure building design-level circularity is discussed. To achieve this goal, a bibliographic-analytical approach is used to analyse the prevalence and alignment of several sustainability and circularity criteria in international policies and standards at the building design level. Finally, the indicators are classified into seven categories: Material and Resources, Energy resources, Water resources, Waste Management, Environment, social and economic indicators. In conclusion, suggestions for further research that have the potential to facilitate the design processes of engineers, architects, and stakeholders are presented. The outcomes of this research can significantly contribute to creating a more circular and, consequently, sustainable built environment.

Keywords: European policies and standards · circularity indicators · building design · the 9Rs framework

1 Introduction

The construction industry consumes more than three billion tons of raw materials [1], and buildings are responsible for 25–40% of the global total energy consumption, contributing hugely to carbon dioxide emissions [2]. Although recent decades have seen many improvements, the built environment continues to be designed around the linear 'take-make-dispose' model, in which materials are sourced, used, and disposed of as waste. This approach results in significant environmental problems. For instance, construction and demolition accounts for 25–30% of all waste generated in the EU3 (France, Germany, and Italy, three large founding members of the European Union) [3]. Additionally,

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buildings in the European Union are responsible for 40% of energy consumption and 36% of greenhouse gas emissions [4]. The solution that the world community agrees on to overcome the negative consequences caused by the built environment is a transition from a linear to a CE. Based on Ellen MacArthur's Foundation (EMF), the CE is a system solution framework that tackles global challenges like climate change, biodiversity loss, waste, and pollution. The CE is also governed by the 9Rs framework, which defines the major strategies that aim to reduce materials use and waste generation and includes ten strategies [5]: R0 (Refuse), R1 (Rethink), R2 (Reduce), R3 (Reuse), R4 (Repair), R5 (Refurbish), R6 (Remanufacture), R7 (Repurpose), R8 (Recycle), and R9 (Recover).

In the CE, design and innovation are critical components of all activities [6]. The design stage is the second phase of the building life cycle, and it is when comprehensive plans for the structure's final design are drawn up, and all the preparation required to begin construction occurs [7]. Regarding the considerations in the design phase, the EMF defines the CE based on three principles, driven by design [8]: 1) Design out waste and pollution; 2) Keep products and materials in use; 3) Regenerate natural systems. A circularity assessment must be done to ensure that the CE principles are implemented. Basically, for any type of assessment, a set of indicators is needed to monitor the implementation of the policies [9].

The standards and frameworks are primarily used to assess the sustainability of the construction, not necessarily the CE. Circularity and sustainability are confused and somewhat interchangeable. According to the U.S. Chamber of Commerce [10], sustainability describes all activities that ensure that human beings can co-exist with the natural world around them. In comparison, circularity is deciding which raw materials go where and how to retain their value for the maximum time. Also, the United Nations Brundtland Commission defined sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" [11]. However, it defines the CE as a new and inclusive economic paradigm that aims to minimize pollution and waste, extend product lifecycles, and broadly share physical and natural assets [12].

Over the past decade, academics, professionals, and governmental officials have shown significant interest in implementing the CE principles within industries that significantly affect the environment, including the construction sector. In this regard, various research studies have been done. In 2021, Rahla et al. [13] reviewed current trends of criteria for building materials to identify selection criteria for building elements according to CE principles through a review of the latest research. Results have shown that little has been concretely achieved in terms of a paradigm shift to CE because the literature focuses on the recyclability of building materials and components at their end-of-life. In 2018, EMF, in cooperation with Arup (a British multinational professional engineering consultant) [14], designed a comprehensive circular building design toolkit to assess the circularity of the building at the design level. The toolkit [14] has a total of 10 indicators, which are based on current international leading policies and guidelines such as Level(s). In another study done in 2019, Corona et al. [15] conducted a review study and critical assessment of current circularity metrics to map methodological developments regarding circularity metrics to identify the foundations of circularity metrics and their applications. The result of the study revealed that none of the assessment frameworks address the CE concept in full, potentially leading to undesirable burden shifting from reduced material consumption to increased environmental, economic, or social impacts.

This study aims to analyse the indicators provided by the standards and frameworks in the construction industry and extract and classify a set of circularity indicators of building design level.

2 Methodology

This study is qualitative comparison-oriented research and aims to analyse the sustainability indicators provided by the international frameworks in the built environment, extracting the circularity indicators of building design level using the 9Rs framework, which defines the major strategies to do the process in an eco-friendly way [13], and finally providing a list of final indicators based on their impact areas.

2.1 Structure and Steps of Analysis

Reviewing the International Framework: A comprehensive study was conducted on international frameworks in construction. Among all reviewed references, frameworks that provide a set of indicators, including Level(s) [16], EN 15804 [17], EN 15643 [18], and ISO 21929 [19], were considered in the analysis.

Screening the CE Indicators: At this stage, it was necessary to identify CE indicators in the sustainability indicators. So, a comparative methodology was adopted to compare all the extracted indicators with the circularity 9Rs framework. The indicators corresponding directly to at least one of the 9Rs were selected as circularity indicators.

Uniformisation of Indicators: References provide indicators that, despite having different names, are used to measure an identical parameter. Therefore, through detailed analysis and comparison of all the indicators, a unification was done to remove the duplicate items and integrate similar indicators.

Categorising the Final Circularity Indicators: The categorisation of the circularity indicators was based on a framework developed by Kubbinga et al. in 2018 [20], which defined the design and construction indicators that promote circular buildings to be integrated into the BREEAM (Building Research Establishment Environmental Assessment Method) [21].

3 Results and Discussion

Regarding the differences between sustainability and circularity, not all the indicators presented for sustainability assessment can necessarily be employed to measure circularity, so in this study, a methodology was defined to extract the circularity indicators from the sustainability ones by the following frameworks.

3.1 Reviewing the International Standards and Framework

Among all the standards and frameworks presented in the field of construction sustainability, four references were reviewed to analyse their circularity streaks in detail as follows, and compliance with 9Rs has also been done.

Level(s)
Level(s) is a common European framework that emerged in 2018 to help construction sector professionals assess and monitor buildings' circularity and sustainability throughout their life cycle. The Level(s) framework comprises 16 indicators, grouped into six macro-objectives belonging to 3 thematic areas [22]. These core sustainability indicators measure carbon, materials, water, health, comfort, and climate change impacts throughout a building's life cycle. Level(s) promote circularity, especially on its macro-objective 2, "Resource-efficient and circular material life cycles," which aims to ensure resource-efficient and circular material life cycles [16]. Figure 1 demonstrates the relationship and frequency of circularity 9Rs with the Level(s) sustainability indicators.

Considering that the most circularity indicators in Level(s) are with emphasis on R2-Reduce, R3-Reuse, R4-Repair, and R5-Refurbish, the circularity indicators of Level(s) are highly compatible with the principle 2 of Ellen Macarthur CE principals which is "Keep products and materials in use."

EN 15804:2012+A2:2019 Sustainability of construction works-environmental product declarations - Core rules for the product category of construction products
EN 15804 is a European Standard under the responsibility of CEN/TC 350, considered the most popular global standard for producing Environmental Product Declarations for construction products [17]. Comparing EN 15804 and the circularity 9Rs framework revealed that these two frameworks share objectives of promoting sustainability, resource efficiency, and circularity in the construction industry. By reviewing the frequency of 9Rs in the indicators of EN 15804, it was found that among all 9Rs, R2-Reduce, R0-Refuse, and R3-Reuse have the most compatibility with the EN 15804 sustainability indicators, which demonstrate the emphasis of this standard in resources use and material conservation, which are compatible with principal 1 and 2 of Ellen Macarthur CE principals "Design out waste and pollution ", and "Keep products and materials in use".

EN 15643 (WI=00350031): Sustainability of construction works-framework for assessment of buildings and civil engineering works
EN 15643 is a series of European Standards under the umbrella of CEN/TC 350 that provide a system for the sustainability assessment of buildings' environmental, social, and economic performances and civil engineering works [18]. The connection between EN15643 and circularity lies in the standard's approach to assessing the environmental performance of buildings, namely through EN15643-2. As shown in Fig. 1, the comparative alignment of the EN15643 indicators with the 9Rs framework revealed that, among all the 9Rs, R2-Reduce, followed by R0-Refuse and R3-Reuse, were the most frequent among the 9Rs.

ISO 21929 Sustainability in Building Construction _ Sustainability indicators. Framework for the development of indicators and a core set of indicators for buildings
The ISO 21929 framework includes a list of critical environmental, social, and economic impact indicators [19]. The connection between ISO 21929 series and circularity lies in the attempt of this standard to introduce a framework for the development of indicators, including a set of environmental indicators, such as using renewable resources, water consumption, and waste production, which are aligned with the principles of the CE. Analysing Fig. 1, R2-Reduce was the most repeated with a frequency of 10, which shows that this standard also emphasises principle 2 of the CE: "Keep products and materials in use".

3.2 Harmonisation of Indicators

By screening all the indicators provided by reviewed references, 56 initial indicators were extracted as circularity indicators (Table 1). In this section, harmonisation was done through a detailed analysis of all indicators to remove duplicates and integrate similar indicators into one.

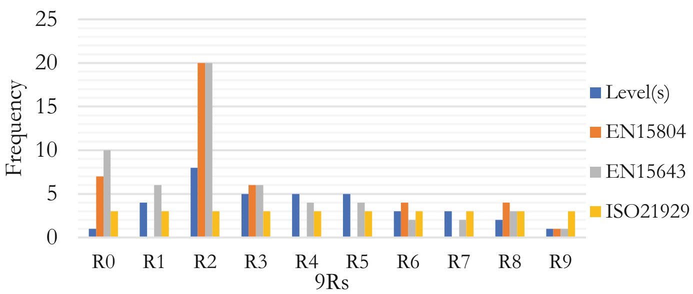

Fig. 1. Frequency of circularity 9Rs in the reviewed frameworks.

As indicator 1 measures the mass of construction products and materials necessary to complete the building, this indicator is classified under the material and resources class [18]. Indicators 2 and 3 measure renewable sources as raw materials (other than energy), so they were unified as the "Use of renewable resources as raw material" indicator. Indicators 4–7 also measure the non-renewable and recycled resources as raw materials. Accordingly, they were unified as "Use of non-renewable resources as raw material". Indicator 8 was considered separate because it refers to reuse, which means using a material with its original function [14]. The indicators 9–11 were merged since they all measure "Non-hazardous waste". The same logic was used to unify indicators 12 and 13, and 14 and 15. Indicator 16 was removed since it was covered under the coverage of other harmonised indicators of this class. Regarding energy resources, indicators 17–19 were merged since they all measure the same parameter. Indicators 20 and 21 refer to renewable primary energy; therefore, they were merged too. The same happened for indicators 22 and 23 since both are to measure renewable secondary fuels. Indicators 24 and 25 also measure the same metric.

Table 1. Harmonisation of the extracted circularity indicators of the building design stage.

Initial indicators	Harmonised indicators
1. Bill of quantities, materials, and lifespans [16]	1. Bill of quantities, materials, and lifespans
2. Use of renewable resources other than primary energy [18]	2. Use of renewable resources as raw material
3. Use of renewable primary energy resources used as raw materials [17]	
4. Use of non-renewable primary energy resources used as raw materials [17]	3. Use of non-renewable resources as raw material
5. Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials) [17]	
6. Amount of non-renewable resources consumption by type (natural raw materials and non-renewable energy) [17]	
7. Materials for recycling [17]	
8. Components for reuse [17]	4. Components for reuse
9. Non-hazardous waste to disposal [18]	5. Non-hazardous waste production
10. Non-hazardous waste disposed [18]	
11. Construction and demolition waste [16]	
12. Hazardous waste to disposal (other than radioactive waste) [18]	6. Hazardous waste production
13. Hazardous waste disposed [17]	
14. Radioactive waste to disposal [18]	7. Radioactive waste production
15. Radioactive waste disposed [17]	
16. Amount of waste generation by type (hazardous and non-hazardous wastes) [19]	Already covered by harmonised indicators 5–7
17. Amount of non-renewable resources consumption by type (natural raw materials and non-renewable energy) [19]	8. Use of non-renewable primary energy
18. Use of non-renewable primary energy [17]	
19. Use of non-renewable primary energy, excluding non-renewable primary energy resources used as raw materials [17]	
20. Use of renewable primary energy [17]	9. Use of renewable primary energy

(*continued*)

Table 1. (*continued*)

Initial indicators	Harmonised indicators
21. Use of renewable primary energy, excluding renewable primary energy resources used as raw materials [17]	
22. Use of renewable secondary fuels [17]	10. Use of secondary fuels
23. Use of non-renewable secondary fuels [17]	
24. Materials for energy recovery [17]	11. Energy recovery
25. Materials for energy recovery [18]	
26. Use of freshwater resources [18]	12. Freshwater consumption
27. Use of net freshwater [17]	
28. Amount of freshwater consumption [19]	
29. Acidification potential [17]	13. Acidification potential
30. Acidification of land and water resources [18]	
31. Abiotic depletion potential for non-fossil resources [17]	14. Abiotic depletion potential
32. Abiotic depletion potential for fossil resources [17]	
33. Eutrophication potential [18]	15. Eutrophication potential
34. Emissions to outdoor air, soil, and water [18]	16. Emissions to outdoor air, soil and water
35. Formation of ground-level ozone [18]	
36. Climate change [18]	17. Global Warming Potential
37. Global Warming Potential [17]	
38. Global warming potential [19]	
39. Life cycle Global warming potential [16]	
40. Ozone-depleting potential [17]	18. Ozone Depletion Potential
41. Destruction of the stratospheric ozone layer [18]	
42. Change of land use [19]	19. Change of land use
43. Design for adaptability and renovation [16]	20. Adaptability potential
44. Change of use or user needs [19]	
45. The ability to accommodate individual user Requirements [18]	
46. The ability to accommodate the change in user requirements [18]	

(*continued*)

Table 1. (*continued*)

Initial indicators	Harmonised indicators
47. The ability to accommodate technical changes [18]	
48. The ability to accommodate the change of use [18]	
49. Maintainability [19]	21. Maintainability
50. Maintenance operations [18]	
51. Resistance to climate change [18]	22. Adaptability for climate change
52. Adaptability for climate change [19]	
53. Design for deconstruction [16]	23. Deconstruction potential
54. Life cycle costs [16]	24. Life cycle costs
55. Life cycle costs [19]	
56. Economic performance expressed in cost terms over the life cycle [18]	

Considering that indicators 26–28 refer to measuring the amount of freshwater consumption, all were merged. Since the indicator of "global warming potential" was more frequent than "climate change" in the reviewed sources, and climate change is one of the consequences of global warming [23], therefore "global warming potential" was chosen as the final indicator. Additionally, the indicator "global warming potential" measures the greenhouse gas emissions associated with the building at different stages along the life cycle [24], and because ground-level ozone (Tropospheric ozone) is the third most important anthropogenic greenhouse gas after CO_2 and CH_4 [24], hence this indicator was merged with the indicator of "Global Warming Potential". On the other hand, indicators 40 and 41 refer to the measurement of Ozone Depletion Potential and were unified. Lastly, "Change of land use" had no identical indicator and was considered separately.

As explained earlier, based on EN 15643-3, indicators associated with adaptability and maintainability are considered under the umbrella of the social aspect [26], so indicators 43–48, which all refer to the adaptability of the building, were unified. Additionally, indicators 49 and 50 both refer to Maintainability. Indicators 51 and 52 refer to the ability to withstand and recover from adverse events or stresses, such as natural disasters and climate change [25], which indicates how buildings are resilient to climate change. Since indicators 54–56 refer to the same issue, they were unified as "Life cycle costs".

3.3 Categorising the Final Circularity Indicators

The classification framework provided by Kubbinga *et al.* [20], which classifies the CE indicators based on two general impact areas (social & technical) and seven classes as seven pillars of the CE, was employed to categorise the indicators (Table 2). As some extracted indicators were not included in the specified categories in the above-mentioned framework due to the nature and impact areas of the indicators, this study made amendments to the mentioned categories and presented a different categorisation.

Table 2. Categories of CE Indicators

Class (Kubina et al. 2018) [20]		Categories developed by this study
Technical	1-Material cycle	1-Material and resources
		2-Waste Management
	2-Energy cycle	3-Energy cycle
	3-Water cycle	4-Water cycle
	4-Biodiversity & ecology	5- Ecosystem
Social	5-Human culture & society	6-Social
	6-Health & well-being	
	7-Multiple forms of value	7-Economic

The 24 indicators were organised into seven categories based on their impact area (Table 3). R2-Reduce was the most frequently extracted indicator, and R7-Repurpose was the least repeated one.

Table 3. The final circularity indicators of the building design level.

Material and Resources	Waste Management	Energy Cycle	Water Cycle	Ecosystem	Social	Economic
Bill of quantities, materials, and lifespans	Non-hazardous waste production	Use of non-renewable primary energy	Freshwater consumption	Emissions to outdoor air, soil, and water	Adaptability potential	Life cycle costs
Use of renewable resources	Hazardous waste production	Use of renewable primary energy		Global Warming Potential	Maintainability	
Use of non-renewable resources	Radioactive waste production	Use of renewable secondary fuels		Ozone Depletion Potential	Design for deconstruction	
Components for reuse		Energy recovery		Acidification potential	Adaptability for climate change	
				Abiotic depletion potential		
				Eutrophication potential		
				Change of land use		

For instance, in this study, the material cycle class is divided into two subclasses of materials and wastes for a more accurate review of the material cycle. Additionally, based on "EN 15643-3, Social aspects [18] indicators associated with Accessibility, Adaptability, Health, comfort, and maintainability are considered under the social aspect and impacts, and therefore this study classified them under the social class.

4 Conclusion

The rapid urbanisation brings challenges like increased waste, resource use, and greenhouse gases. In response, policymakers and scholars are investigating the (CE) model, which aims to enhance resource management and efficiency while reducing waste, addressing these urgent concerns.

This study aimed to analyse the international sustainability frameworks in construction and provide a list of circularity indicators for the building design stage. The findings revealed that among the 107 analysed indicators, more than 50% of them, which count for 56, were directly associated with circularity within the building design stage, which ultimately were summarised into 24 final indicators following unification. Results also revealed that although the reviewed references mainly refer to sustainability indicators and none of the approaches fully address or directly mention the CE concept, they align partially with CE principles, demonstrating an interconnecting relationship between circularity and sustainability that shows CE cannot be fully separated from sustainability. Additionally, among all 9Rs, R2-Reduce was the most frequent one, followed by R0-Refuse and R3-Reuse, respectively, for the most frequent strategies, while R7-Repurpose was the least important one. This led to the conclusion that the provided reviewed indicators mostly emphasize "design out waste and pollution" and "keep products and materials in use", which are respectively 1st and 2nd principles of EMF circular design principles.

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Unlocking the Potential of Material and Building Passports in the Transition to a Circular Economy in Buildings: A Critical Review

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Abstract. The transition towards a Circular Economy (CE) stands as a pivotal strategy in reshaping our prevailing consumption patterns towards more sustainable resource management. Within this context, the European Union places a strong emphasis on elevating recycling and renovation rates while reducing dependence on primary resources, with a particular focus on the construction industry. Material and Building Passports have emerged as potential tools to facilitate this transition. They play a multifaceted role in CE, serving to raise awareness of the building's performance, functioning as digital repositories of extensive data, and acting as consulting instruments for stakeholders involved in renovation actions, energy management, and building operation. However, a universally accepted definition of these tools remains elusive, and diverse interpretations persist. To contribute to a deeper understanding of these tools, this study embarks on a comprehensive review, tracing their evolutionary journey and delving into the potentialities and synergies they offer in fostering circularity throughout the life cycle of buildings. It also examines the barriers hindering their full-scale development and adoption, including the lack of standardization and legislative measures, financial constraints, issues of stakeholder involvement and responsibility, as well as challenges associated with data accessibility.

Keywords: Circular Economy · Building Passport · Material Passport · Construction Industry · Digital Building Logbook

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1 Introduction

In the context of the escalating global imperative to address climate change and environmental sustainability, decarbonization by 2050 constitutes a central focus within the European Union's overarching strategies for the upcoming years [1]. At the heart of this vision lies the Circular Economy (CE) strategy, which seeks to maximize recycling and renovation rates to reduce dependence on primary resources. This initiative aligns with the objectives of the European Green Deal and the 2030 Agenda for Sustainable Development.

The construction sector stands as one of the largest consumers of energy and is accountable for 40% of global CO2 emissions [2], along with being responsible for 60% of the global consumption of raw materials [3]. Despite the significant impact of this sector on both energy consumption and raw material use, there is a pressing need to accelerate building renovations. Current rates of energy renovations in the European Union (EU) hover around a mere 0.2% on average. In contrast, the EU has set ambitious targets to double these figures by 2030, also fostering deep renovations [4].

In this context, the present study focuses on exploring and analyzing the relevance and potentials of Material and Building Passports (MPs and BPs) in the transition towards a CE. These passports not only provide an effective tool to raise awareness about building performance among all stakeholders involved but also enable the digital storage of critical information, facilitate stakeholder consultation prior to any renovation action, and contribute to efficient energy management and recording of building operations. Thus, the novelty of this paper lies in the examination of the contribution of these passports at each stage of the building life cycle.

This study is situated within a growing body of literature that underscores the importance of MPs and BPs in the transition towards the CE and builds upon systematic reviews and analyses of the digital tools' applications, which are being recognized as key elements in this process.

2 Methodology

The research aims to underscore the significance of MPs and BPs in promoting circularity in buildings across various life cycle stages. To achieve this objective, the study conducts a comprehensive state-of-the-art analysis on these concepts, elucidating their distinctions and applications in supporting sustainable and circular practices in the building sector. The analysis encompasses the origins and definitions of MPs and BPs, and historical developments. The primary focus of the paper is on examining the roles and opportunities presented by passports in the building sector. The research delves into the capabilities of passports across four key life cycle stages of buildings: 1) Design stage, 2) Construction stage, 3) Operation and maintenance, and 4) End-of-Life (EoL) management. This examination explores how passports can facilitate closed loops and circular feedback systems, thereby enhancing the efficiency of management practices and fostering connections among stakeholders. The discussion section sheds light on the multidimensional barriers that impede the widespread adoption of passports and identifies potential opportunities to address them. By presenting a nuanced discussion on the challenges, opportunities, and future prospects, the research contributes to a more thorough understanding of the role of passports in advancing circularity in the building sector.

3 State-of-the-Art of Material and Building Passports

Building Passports have been present in Europe for several decades, with their roots tracing back almost 30 years to the mid-90s. The first BP initiatives emerged in Germany [5] and Denmark, where the "Det digitale energimærke" was introduced [6]. Despite the prolonged existence of these initiatives, there is no universally agreed definition of the tool. Different regions in Europe have adopted varying approaches, encompassing aspects from energy performance to technological data [5]. However, what appears to be widely accepted is that BPs serve as tools providing relevant information about buildings to diverse stakeholders within the building sector. The specifics of content and format, nevertheless, vary across different initiatives.

With the surge in renovation activities, a new iteration of these passports has emerged, known as the "Building Renovation Passport" (BRP) [5]. This version is specifically tailored for existing buildings undergoing staged renovation. Although there is no single model for this tool, there is a consensus that it should consist of two key parts: a digital building logbook (DBL) that compiles all information about the building and a renovation roadmap that guides the owner through the necessary steps to transform buildings into zero-emission ones by 2050 [7].

Unlike the BP, which was primarily associated with national or regional initiatives, the BRP has been included into European legislation due to its potential to catalyze building renovation. In 2021, the first version of the proposal for the recast of the Energy Performance of Buildings Directive (EPBD) officially agreed on a definition—this definition was slightly modified in the 2023 amended version of the Directive [7]. Additionally, an agreed common scheme will be developed soon to be applicable to all EU Member States (MS).

Simultaneously, there have been recent developments in the creation of another building-related passport system known as the Material Passport (MP). MPs are designed to collect and store data on the materials constituting buildings, offering valuable insights for assessing the circularity of buildings and facilitating decision-making regarding recovery, recycling, and reuse [8]. According to van Capelleveen [9], the earliest reference to this passport concept dates back to O'Shea [10], where it was initially referred to as the Product Passport (PP). Presently, this concept is being incorporated into European legislation under the designation of Digital Product Passport (DPP), with its definition and content outlined in the proposal for a new Ecodesign for Sustainable Products Regulation (ESPR). The DPP doesn't exclusively concentrate on building materials but encompasses them within its broader scope.

According to Buchholz and Lützkendorf [11], MP can function independently or be integrated into a multifunctional system, such as the mentioned DBLs. In alignment with this concept, the European Commission (EC) is currently in the process of developing the DBL to serve as comprehensive repositories, encompassing not only data but also documents and certificates related to buildings, such as Energy Performance Certificates

(EPCs), BRPs, and MPs-DPPs [7]. However, connecting all these records into a single repository or gateway is highly complex due to factors such as format compatibility and the lack of interoperability of some data sources [12].

Observations reveal that, despite numerous advancements, a common definition for the diverse tools in question has yet to be established. Regarding the BRP, the 2023 proposal for the EPBD recast stipulates that by the end of 2024, MSs shall introduce a scheme. To achieve this, a common European framework is expected to be adopted by the end of 2023.

Turning to the European DBL, which emerged as an independent tool in the Renovation Wave, several advancements have already been made, both by the EC and independent studies or research projects [13]. However, a universally agreed-upon model is still absent, and new models are emerging based on new functionalities proposed for the DBL [14, 15]. Despite the near-term implementation appearing unlikely due to numerous existing barriers that require resolution, the 2023 proposal for the EPBD recast states that by the end of 2024, the EC will establish a common template for the tool.

Regarding the MP, it is evident that various alternative terminologies such as Product Passport, Resource Passport, Recycling Passport, Cradle-to-cradle Passport, etc., are used to refer to this phenomenon. This diversity in nomenclature underscores a lack of homogeneity and definition thus far. We suggest that these passports can best be defined as a digital interface composing a certified identity of a single identifiable product by accessing the set of life cycle registrations linked to this object to yield insight into the sustainability and circularity characteristics [9].

Within the ongoing process of establishing criteria for defining these tools, it becomes imperative to clarify their potential and role in driving the transition towards a CE in the context of building construction.

4 The Role and Potential of Material and Building Passports in Promoting Circularity in Existing and New Buildings

MPs serve as digital interfaces, encapsulating the verified identity of singular products. This identity is established by accessing a comprehensive set of life cycle registrations associated with the object. The primary purpose is to provide insights into the sustainability and circularity characteristics, circular value estimation, and circular opportunities for both the product and its underlying components and materials. MPs play a pivotal role in advancing circularity across various scales, ranging from individual materials through buildings to entire urban clusters. At the building scale, they function as crucial tools supporting circular practices throughout the building's life cycle—from design to construction to operation until EoL management.

BPs, on the other hand, are associated with a specific building, accompanying it throughout its lifespan. They contain data enabling its comprehensive description and characterization, while also documenting any alterations or interventions made to it. Moreover, BPs serve as a point of access to all external documents related to the building.

The following sections analyze the potential of MPs and BPs in all the stages of a building's life cycle.

4.1 Design Phase: New Buildings and Renovation

Despite their utility across all stages of a building's life cycle, the optimal utilization of MPs involves their meticulous preparation and integration during the design phase. This strategic incorporation enables the creation of specific scenarios, empowering informed decision-making regarding data management and governance throughout the entire life cycle of the building.

Utilizing MPs during the design phase ensures that all materials and components are purposely designed for easy reuse, recovery, and repair in subsequent life cycle stages. This approach conceptualizes buildings as material banks, optimizing design while minimizing the use of primary resources and contributing to a waste-free CE. The novelty of MPs lies in their ability to determine embedded materials, thereby aiding in design optimization. MPs also contain extensive information, including physical, chemical, and biological characteristics, material health data, transportation details, and additional information for effective evaluation and certification [16]. Furthermore, MPs incorporate material cost information, facilitating overall cost calculation from the design stage. This supports economic decision-making, including assessing the economic viability of a building and other economic aspects over its entire life cycle. This comprehensive approach helps determine the necessary monetary input to improve the sustainable and circular performance of the building model [17].

In addition to containing and linking all the information that characterizes the materials and products constituting buildings, compiled through MPs, BPs, and DBLs allow the characterization of many other aspects. The design phase emerges as the opportune time for developing BPs, BRPs, and DBLs, generating valuable information that proves highly useful in subsequent phases of the building's life cycle.

In the specific case of the design for a renovation, the BRP is of great relevance. As mentioned before, BRPs consist of a DBL, which doubles as an independent data repository and a renovation roadmap. The DBL empowers professionals with essential building information collected during or prior to the design stage, facilitating the design for renovation. Concurrently, the renovation roadmap provides guidance to property owners throughout the staged renovation process.

A significant nexus arises between the DBL and the MP, advocating for the inclusion of a material inventory in the DBL, functioning akin to a MP.

Furthermore, the design phase generates substantial information about materials and products slated for use during the building's construction phase. In this context, BPs, especially DBLs, serve as ideal repositories for storing such information. The stored data proves instrumental during the building use, maintenance, future interventions, and eventual deconstruction.

To harness the full potential of passports from the design stage, integration with other technologies, particularly Building Information Modeling (BIM), is common. The incorporation of MPs and BPs into BIM models presents a promising avenue for enhancing sustainability and circularity in the construction sector. The generation of BIM-based MPs and BPs facilitates real-time updates, enabling their use for optimization in early design stages, and fostering increased awareness of recyclability and reusability in construction [17]. Leveraging BIM's capabilities enables stakeholders to make more informed decisions aligned with the principles of the CE.

4.2 Construction Stage

Within construction processes, a considerable volume of supplementary information is generated, distinct from the design stage. This information originates from suppliers and subcontractors in diverse forms and levels of detail. Apart from traditional plans and information about materials and products, there is an emerging trend to incorporate laser scans of the building, proving beneficial for the creation of passports at both the building and element levels [18, 19]. BPs and DBLs function as optimal repositories for systematically storing this data, ensuring that maintenance operations and subsequent interventions are well-informed and aligned with the building's history.

An especially noteworthy context for the implementation of MPs and BPs is found in the realm of industrialized construction [20], wherein the manufacturing process occurs off-site while the assembly takes place on-site. This assembly process generates a substantial amount of data [21], which is crucial in anticipation of the eventual disassembly [22, 23] and recycling of building components.

Beyond their role in generating and storing information, BPs and MPs also contribute to on-site quality control by documenting details regarding the quality standards and specifications of materials. This documentation aids in the construction of structures that are durable and resilient. In the same way, these data also assist in assessing compliance with environmental regulations and standards.

Additionally, waste generation during the construction phase may arise from design faults, on-site errors, workflow confusion, unanticipated plant breakdowns, and rehabilitation [24–26]. Intelligent waste recycling management play a crucial role in enhancing supply chain construction plans.

4.3 Operation and Use of Buildings

During the operation and use stage, MPs and BPs present significant potentials related to predictive maintenance, management, and optimization of building performance.

In the context of building maintenance, MPs offer a comprehensive overview of the building components, encompassing details on materials' durability, expected lifespan, and recommended maintenance practices. This information is invaluable for promptly identifying and resolving issues. Additionally, it opens up the possibility for BPs and the DBLs to function as user-friendly maintenance manuals [27].

Passports also play a vital role in improving the energy efficiency of buildings. They not only furnish details on the thermal properties of components but also serve as repositories for data gathered through smart monitoring. These data, when integrated with Artificial Intelligence (AI), enable the automation of the building systems and the optimization of their energy consumption while improving thermal comfort [19].

Finally, MPs, BPs, and DBLs serve to provide and circulate information among stakeholders involved in each stage of the chain. This ensures proper management to support decision-making regarding acquisition, maintenance, and user requirements.

However, despite the effectiveness of BP and MPs as data repositories and "gateways" during this stage, data acquisition remains a primary challenge. As stated by Gómez-Gil et al. [13], a large amount of data is generated throughout a building's lifespan, yet there is a general lack of strategies to manage and correlate this data. In fact, currently, the actual data used for facility management is handled on a day-to-day basis with no general data storage or accessible memory repositories.

4.4 End-of-Life, Recycle, Reuse and Construction, and Demolition Waste Management

MPs and BPs play a crucial role in fostering circularity during the EoL stage of a building and managing the waste produced during its demolition or deconstruction. Comprehensive knowledge of all the materials that constitute a building, along with their properties and quantities, as well as all the building's components, provides technicians with the ability to systematically organize the demolition or deconstruction procedure. This foresight allows for the meticulous predetermination of materials and components that can be reused, recycled, or recovered, even from the design stage.

To be more specific, MPs and BPs in conjunction with new technologies, such as BIM, can be capitalized on verifying the optimum demolition or deconstruction procedure along with the most efficient construction and demolition waste (CDW) management to be followed [28]. Regarding the materials and components resulting from a demolition process, a cost-benefit analysis can demonstrate the most suitable management activity (e.g., upcycling, reuse, recycle) for each specific one. Making use also of other advanced technologies, the optimum transportation path of the produced waste can be also defined to further improve the circularity and sustainability efforts [29].

Focusing more on MPs, validated models promoting effective CDW management can be detected in the international literature [30]. In a referenced study, researchers integrated sustainability assessment indicators in MPs. Another project developed a BIM-based MP to evaluate both the recyclability of a building's materials and their environmental footprint after the building's demolition [31]. However, the researchers acknowledge the need for additional properties to be considered in their MP for a more holistic approach, such as the reusability of materials.

5 Discussion and Conclusions

MPs and BPs serve as valuable tools throughout all stages of a building's life cycle, enabling the collection, storage, and sharing of substantial amounts of building-related data, including general information, architectural survey/geometry, construction details, material inventory, predictive maintenance plans, features of building systems, accessibility conditions, what-if analysis, performance optimization, real-time energy use measurement, behavioral insights, water resources assessment, health and comfort evaluation, and life cycle optimization.

On the one hand, the evolution of the BP has lied the foundation for standardized assessment of energy performance in buildings. On the other hand, the MP has not been reached the same level of granularity. Despite notable individual examples, such as the BAMB2020 - Building As Material Banks initiative, there lacks a comprehensive international standard for indexing the circularity of building materials. Thus, as these tools are taking shape, it was crucial to emphasize their potential to promote circularity throughout the entire life cycle of buildings.

Despite the acknowledged importance of MPs and BPs, their widespread applications are hindered by various factors. Challenges include the absence of legislations and standards that support their use, unclear guidelines on their structure and management, and issues related to governance and ownership, including the aspect of data ownership and privacy protection.

Another barrier to the implementation of these tools is the scarcity of data, especially regarding materials from existing buildings, and the lack of shared information about materials, particularly on LCA and EoL [32, 33]. While there are numerous common databases that provide valuable information to feed BPs, such as national cadasters, land registries, or EPC registries, in some countries there are different sources at smaller levels, which makes it hard to create a complete picture of the situation in Europe. Furthermore, some of those sources are either not interoperable or do not collect sufficient data, which is why new data sources have been identified in the literature. They include new technologies for data acquisition, such as 3D scanning or smart monitoring, and upcoming EU tools, such as the Level(s) framework or the Smart Readiness Indicator, which are called to generate valuable data [12].

To implement these passports and distribute responsibilities for them, including their maintenance and the management of financial and production chains, a high level of collaboration among stakeholders is required. Financial barriers further compound the issue, as both capital and operational costs are high. Despite the potential long-term benefits, value chain stakeholders often perceive the initial costs as unjustified, particularly in the context of profitable businesses. Lastly, the overall adoption of digital technologies and tools, including MPs and BPs, is impeded by a lack of knowledge about their applications and capacities. Achieving a widespread understanding among actors is crucial for utilizing these tools effectively and leveraging their potential to support sustainable and circular practices in the built environment.

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Towards Circular Building Key Performance Indicators

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Abstract. The concept of circular economy (CE) nowadays garners considerable attention as strategy for resource management and waste reduction. The principles of circular economy have emerged as a promising framework for minimizing environmental impacts while maximizing resource efficiency across the entire life cycle of a building. To effectively assess and monitor the progress towards circularity in buildings, the development and implementation of appropriate key performance indicators (KPIs) are crucial. This paper provides a comprehensive overview of circular economy KPIs in the building sector, aiming at supporting industry professionals, policymakers, and researchers in understanding and implementing effective measurement and evaluation frameworks. The study identified several indicators related to circular buildings and categorized them based on building types and layers. The study findings indicate lack of robustness to comprehensively evaluate the circularity and socio-economic impacts of circular practices that highlight the need for more comprehensive and universally accepted KPIs. Such indicators could guide stakeholders, enabling them to assess progress towards circularity, identify areas for improvement, inform their decisions, and actively promote the transition towards more circular building practices.

Keywords: Circular Economy · Key Performance Indicators · Buildings

1 Introduction

The construction industry plays a crucial role in fostering economic development. However, the construction sector's linear economic model is accountable for greenhouse gas emissions, natural resource depletion, and waste production [1]. In response to these pressing concerns, the concept of CE attracted significant interest as a solution to address environmental and economic issues as the concept offers an alternative to the traditional linear economy of "take-make-use-dispose".

According to the Ellen Macarthur Foundation [2], CE is defined as "*An industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business*

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models". CE encourages the design of buildings that have a circular flow of materials throughout their lifecycle, involving procurement, utilization, deconstruction, reutilization, recycling, and resource recovery. Leising et al. [3] described CE for buildings as *"a life-cycle approach that optimises the buildings' useful lifetime, integrating the end-of-life phase in the design and uses new ownership models where materials are only temporarily stored in the building that acts as a material bank"*.

Monitoring and evaluation tools are crucial for effectively transitioning to CE, as it enables organisations to track progress and make informed decisions for achieving circularity goals [4–7]. According to the Organisation for Economic Co-operation and Development (OECD) [8], an indicator is defined as "a *quantitative or qualitative factor or variable that provides a simple, and reliable, means to measure achievement, to reflect the changes connected to an intervention, or to help assess the performance of a development actor*". Megevand et al. [9] added that indicators play an important role in simplifying information, as they condense complex phenomena into measurable and quantifiable metrics and are capable of effectively communicating and raising public awareness about significant issues. In addition, Indicators contribute to decision-making by offering a simplified and accessible representation of relevant information, allowing decision-makers to make informed choices without requiring extensive details and analysis [7, 10]. Developing successful indicators for policymaking involves finding a balance between several factors. This includes considering the need for conceptual simplicity, the cost of evaluation, and the alignment of the indicator with existing policy targets [11].

This study presents a systematic review focused on the KPIs for circular buildings. The main objective of the study is to identify KPIs for assessing progress toward circular building practices and compare their level of effectiveness in terms of source data and applicability to different layers of buildings. The research questions formulated for this study are:

1. What are the KPIs related to the circular design and construction of buildings?
2. How are the KPIs currently used in the evaluation of circular building practices?

2 Methodology

The primary objective of this study is to undertake an extensive literature review to identify circular buildings' KPIs. To achieve this objective, a thorough search was conducted using two prominent academic databases: Scopus and Google Scholar. The aim of this research is to investigate the KPIs of CE in buildings. To conduct this investigation, a set of key words were employed including "Circular Buildings", "Key performance indictors", "Circular Indicators", "Circular Economy Indicators", "Circular Construction" OR "CE", "KPIs". The search focused on articles published in English from 2013 to 2023. To fully understand the current state of the field, the study employed both qualitative and quantitative research methods. This review synthesizes a wide range of research methods, from case studies to mixed methods and theory development.

The search results were initially transferred to an Excel spreadsheet. Following, full-text access was obtained for the most relevant studies, and titles, and abstracts were examined for shortlisting, applying specific search criteria to include or exclude papers based on their alignment with the research topic. To evaluate the quality and relevance of the articles, the following questions were posed:

1. Does the article align with the review's objectives
2. Is the article clearly focused on KPIs for CE?
3. Could the identified KPIs be implemented in the building sector?

Finally, a comprehensive full-text evaluation was conducted to assess the quality and relevance of the remaining articles which resulted in 40 articles being included in this study. Figure 1 shows the phases completed for processing published papers.

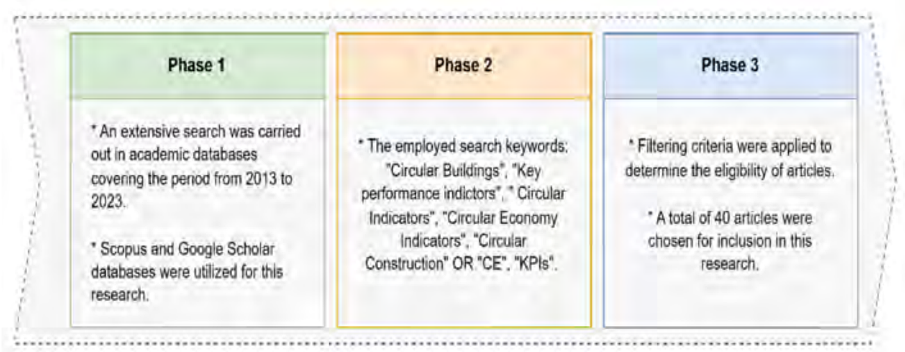

Fig. 1. Phases in processing published papers.

3 Circular Economy Indicators

Circularity can be evaluated through the utilization of various circular indicators. Moraga et al. [12] defined a circular indicator as *"a variable (parameter) or a function of variables to provide information about circularity (technological cycles) or the effects (cause-and-effect modelling)"*. Indicators for measuring the circular economy can be categorized into three levels: macro (global, national, regional, city), meso (industrial symbiosis, eco-industrial parks), and micro (individual firm, product) [6, 13, 14].

Saidani et al. [15] identified a set of 55 indicators developed by scholars, governmental agencies, and consulting companies and clustered them into 10 categories of taxonomies. The Ellen MacArthur Foundation and Granta Design [16] published Material Circularity Indicators (MCI) which is a micro level index that allows companies to evaluate the degree to which the material flows of a product are restorative, indicating how efficiently resources are circulated and reused within the product's lifecycle. Kristensen et al. [6] reviewed 30 circular indicators at the micro level and stated that most indicators focused on recycling, end-of-life management, or remanufacturing. Parchomenko et al. [17] used Multiple Correspondence Analysis (MCA) to evaluate 63 CE metrics based on 24 elements relevant to CE, such as recycling efficiency, longevity, and stock availability. The study's findings indicated that the most prevailing CE perspectives focus on waste disposal, differentiation between primary and secondary resource usage, resource efficiency and productivity, as well as the efficiency of recycling processes. Oliveira et al. [18] examined a total of 58 indicators and indicated that many of these metrics are environmentally driven indicators at the nano level, emphasizing material and resource recovery strategies and rarely address social aspects. However, Moraga et al. [12] claimed that determining the specific indicators and metrics to assess progress toward a CE can be challenging due to the ambiguity of the concept which could lead to incoherent conclusions.

4 Circular Buildings KPIs

According to Pomponi and Moncaster [19] buildings can be considered at meso level, while building components at micro level, as shown in Fig. 2. Circularity indicators can help to evaluate buildings and products during three phases of their lifetime: construction, use, and end-of-life [20]. Several authors have identified a range of CE indicators for buildings, for example, Khadim et al. [7] conducted an extended systematic literature and identified a total of 24 distinct building circularity indicators. The authors claimed that the most widely adopted KPIs are material loops, disassembly, adaptability, and reusability. Bilal et al. [21] completed a detailed literature review and consulted 21 experts from 14 different countries to select and rate the most important indicators related to CE. The results were then used to identify the top 24 indicators. Verberne [22] developed the Building Circularity Indicator (BCI) for the construction sector which focuses on identifying and evaluating KPIs designed to measure CE aspects within the built environment.

According to Brand [23], building can be divided into six shear layers (6 S's): site, structure, skin, services, space, and stuff, based on the rate they experience change and their role in keeping the building alive. Most KPIs identified in Table 1 measure circularity across structure, skin, services, and space, as their life cycle is less or equal to the life cycle of the building. Some of the indicators follow a more holistic approach and include the site in the calculation of building KPIs. For instance, FLEX 4.0 indicator [24], considers multifunctionality, expandability, and area coverage efficiency of the site in calculating building KPI, which is based on design for adaptability considering 44 flexibility performance indicators. Another indicator: RIPAT 1.0 by Valdebenito et al. [25] also included site geology and seismic characteristics in calculating the circularity of building sites.

Circularity in building structures is assessed through various KPIs, with a primary emphasis on optimizing space, improving accessibility, and minimizing obstacles posed by structural elements, to align with circular design principles [24]. Building skin is also covered by almost all the KPIs. A few of the metrics related to building skin in these indicators include the level of efficiency of façades, windows, and daylight facilities [26]. The level of circularity in services is usually measured in terms of measures and control of services, and their modularity and abundance [26]. The distribution, accessibility, and independence of user facilities are also gauged to quantify circularity in building services [24]. Lastly building space is gauged in terms of circularity based on its effective functionality and accessibility [26], the ease of dismounting, and the flexibility of units like infill walls, ceilings, and floors [24]. The stuff is items like furniture and electronics, that move around the building frequently are usually not included in the calculation of the building circularity KPIs. Their circularity is usually gauged by product circularity indicators.

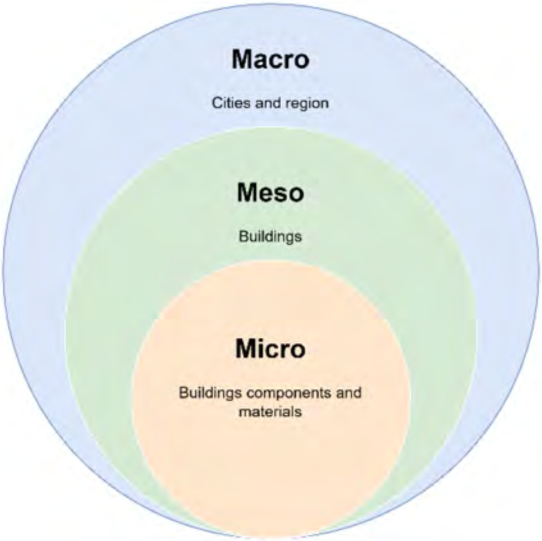

Fig. 2. Circular economy indicator levels.

The application of various KPIs suggested in the literature also varies depending on the size of measurement (material, product, or building), the kind of building (residential, commercial, or historical), and the stage of study (existing or new buildings). Tables 1 and 2 show the identified indicators that apply to all types of buildings with few of them limited to be used for certain types of buildings only. It's important to highlight that certain elements in Table 1 are not explicitly formulated as indicators; instead, they are presented in the form of frameworks. These frameworks are based on studies that have demonstrated their effectiveness in developing building indicators. For instance, Dodd et al. [27] illustrated how 'Levels,' essentially a framework for assessing and reporting sustainable performance, can be utilized to create specific building-level indicators.

Some of them directly use the Building Information Modelling (BIM) [28, 30, 32], while others are reported in the form of quantitative measures [29, 37–39]. Whole-Building Circularity Indicator (WBCI) by Khadim et al. [38] uses only quantitative data that can be processed in any spreadsheet tool. WBCI considers 4 material flow phases of the building: manufacturing, construction and assembly, use/operation, and end of life. Lei et al. [39] used reliability theory to create an overall CE index that includes circularity and sustainability indices. Cottafava and Ritzen [14] proposed a Predictive Building Circularity Indicator (PBCI) which helps understanding how design for disassembly criteria impact on circularity. Zhai [28] developed a BIM-based framework that conducts the circularity assessment throughout the building's design phase using Autodesk Revit and Dynamo for Revit. Within the same framework, BIM may be used to automate the circularity assessment due to its capabilities in parametric modelling, data classification, and visualization.

Table 1. Analysis of Circular Building KPIs.

Study	Building KPI	Type of Building	Building layer applicability				
			Site	Structure	Skin	Services	Space
Dodd et al. [27]	Level(s)	Residential and office buildings	✓	✓	✓	✓	✓
Zhai [28]	BIM-Based Building Circularity Assessment	All buildings (design phase only)		✓	✓	✓	✓
Schaik [26]	Modified Alba Concept (For Foundations)	Building foundation only		✓			
Cottafava and Ritzen [14]	Predictive Building Circularity Model	Residential buildings	✓	✓	✓	✓	✓
Madaster [29]	Madaster Circularity Indicator	All buildings	✓	✓	✓	✓	✓
Geraedts [24]	FLEX 4.0	General and office, school	✓	✓	✓	✓	✓
Di Biccari et al. [30]	Circular Business Models (CBM) Based Circularity Indicator	All buildings			✓		✓
Sreekumar [31]	Integrated Energy Performance and Circularity	New buildings		✓	✓	✓	
Akanbi et al. [32]	BIM-based Whole-life Performance Estimator	All buildings		✓	✓		✓
Fregonara et al. [33]	Synthetic Economic Environmental Indicator	Existing buildings		✓	✓		

(*continued*)

Table 1. (*continued*)

Study	Building KPI	Type of Building	Building layer applicability				
			Site	Structure	Skin	Services	Space
Valdebenito et al. [25]	RIPAT 1.0	Heritage Buildings	✓	✓	✓		✓
Kubbinga et al. [34]	Framework for Circular Buildings	All buildings		✓	✓	✓	✓
BAMB [35]	Circular Building Assessment Prototype	All buildings		✓	✓	✓	✓

There are different ways of using the circular building KPIs reported in the literature.

There are also specialized software tools available to analyse the level of circularity of a building, for which the user is essentially required to input both quantitative and qualitative data. C-CalC [36] is one of those which uses both quantitative and qualitative data to calculate a building's circularity and compares it against other structures. It emphasises the method, the degree of adaptability, and the utilization of materials. In contrast, Oliveira et al. [18] argued that the analysed indicators primarily concentrate on material and resource recirculation, lacking the robustness needed to effectively assess the overall sustainability performance of a circular system.

Table 2. Analysis of Circular Building KPIs (continued).

Study	Building KPI	Type of Building	Building layer applicability				
			Site	Structure	Skin	Services	Space
Cenergie [36]	C-CALC	All buildings		✓	✓	✓	✓
Dams et al. [37]	Circular Construction Evaluation Framework	All buildings		✓	✓	✓	✓
Khadim et al. [38]	Whole building circularity indicator	All buildings		✓	✓	✓	✓
Lei et al. [39]	Probabilistic circular economy assessment of buildings	All buildings		✓	✓		✓

According to Di-Maio and Rem [11], policymakers continue to face challenges in finding an effective key performance indicator, and the existing indicators often fall short in properly capturing the broader socio-economic impacts of circular practices. Mesa et al. [40] argue that indicators for measuring CE are currently in the early stages of development. According to Khadim et al. [7] circular indicators in the construction sector are not well-established yet. As a result, current indicators do not raise confidence or trust among construction practitioners and policymakers.

5 Conclusions

CE offers promising solutions to the unsustainable "take-make-use-dispose" model currently prevalent in the building industry. The shift to CE is largely dependent on monitoring and assessment instruments such as KPIs, which allow decision-makers to evaluate circularity and make well-informed decisions. Notwithstanding, the creation and implementation of these KPIs in the framework of circular building practices present various difficulties often linked to conceptual clarity, evaluation cost-effectiveness, and compatibility with current policy objectives.

The purpose of this investigation was to examine KPIs pertinent to circular building practices, aiming at assessing the extent to which circularity is integrated into the built environment. The study identified several KPIs that can help to gauge the level of circularity in buildings. These indicators, once categorized according to building type (residential, commercial, or historical), stage of existence (existing or new buildings), and number of building layers (structure, skin, space, etc.), provide valuable insights into diverse aspects of circular building practices.

Despite valuable findings, we recognise persistent limitations for the full implementation of CE being the main one that current indicators lack robustness to comprehensively evaluate the circularity and socio-economic impacts of circular practices. This concern raises questions about the effectiveness of current assessment frameworks, therefore suggesting the need for a more holistic understanding of the broader implications of circularity in building practices. Finally, to effectively drive the shift toward circular building practices, more comprehensive and widely accepted KPIs are required, as the identified gaps limit the level of confidence and trust placed by practitioners and policymakers regarding the effectiveness of current indicators.

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Axiomatic Design and Design Structure Matrix for Circular Building Design

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Abstract. The study aims to propose the integration of Axiomatic Design (AD) and Design Structure Matrix (DSM) methods to support the implementation of building reversibility within circular building design (CBD). In CBD, strategies for building reversibility have been formulated, but available tools mainly support design evaluation in the late stages. On the other side, in engineering design, methods to support reversibility in early design stages are available. AD and DSM are two matrix-based product modelling methods that are used in the analysis and modelling of relations in complex systems from the concept design. AD guides the designers in modelling the relationships between functional elements and physical components in a structured manner from the early design stages. DSM provides a method for modelling physical relationships among the physical components and groups them into modules. Despite the potential benefits of using these matrix-based design methods, previous studies on building reversibility within CBD have not yet explored this proposition. The study intends to place the theoretical premises for the application of AD combined with DSM within CBD for building reversibility. The study applies theory-oriented research by exploring, collecting, and evaluating relevant information from different theoretical and practical sources to formulate propositions on building reversibility within CBD. Propositions will be tested in future real-world applications while detecting challenges and limitations to assess effectiveness in supporting building reversibility within CBD.

Keywords: circular building · building reversibility · matrix-based product modelling methods · Axiomatic Design · Design Structure Matrix

1 Introduction

Circular building design (CBD) has recently achieved interest and recognition because of its potential for sustainable development in the built environment through the application of the circular economy approach to building systems, components and materials. Within CBD, building reversibility concepts and design strategies have been formulated to support the implementation of circular building solutions. However, this theoretical content is not yet fully embedded within design frameworks and tools to support the design process. The lack of design tools for the development of circular buildings through design strongly limits the application of circular strategies in the building sector [1].

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On the other side, in engineering design, methods to support product reversibility in early design stages are available. AD and DSM are two matrix-based product modelling methods increasingly being used for reversibility in complex systems through modelling relations since the concept design stage [2].

The study aimed to define the theoretical propositions to support building reversibility within CBD by combining AD and DSM. Despite the potential benefits of matrix-based product modelling methods, previous studies have not yet considered the proposition of combining AD and DSM for building reversibility within CBD. Thus, the objective of this study was to provide theoretical premises on the application of AD-DSM to support building reversibility within CBD.

The research questions were the following:

1. What is building reversibility within CBD?
2. How is building reversibility supported by design tools within CBD?
3. Can AD-DSM methodology support building reversibility within CBD?

The research objectives were defined as reported below:

1. define building reversibility within CBD and how to implement it in design by a literature review.
2. analyze and compare existing design tools within CBD to support building reversibility and define existing gaps.
3. analyze AD-DSM theory to show potential to fill gaps in building reversibility within CBD and define propositions to be tested in future by applications.

The study consisted of theory-oriented research aiming at contributing to theory development by exploring design methods that can support the implementation of building reversibility within CBD. The study was conducted through exploration by collecting and evaluating relevant information from different theoretical and practical sources to formulate propositions and assess how exactly they could best contribute to CBD. This information came from different sources concerning the object of study (insights from existing research, and the researcher's experiences). This theory-oriented research started with an exploration of theory and practice to find available propositions regarding building reversibility within CBD. Relevant propositions were finally formulated for being tested in future research to show evidence of their relevance, define challenges and limitations, and potentially advance the theory in CBD.

The paper is structured as follows. Section 1 provides definitions for building reversibility in a circular building, related design frameworks, their comparison for integration and the analysis of available design tools for building reversibility within CBD. Section 2 provides an introduction to matrix-based product modelling methods and an overview of AD and DSM and their combination for building reversibility in CBD. Finally, Sect. 3 formulates propositions for future research and conclusions.

2 Building Reversibility Within Circular Building Design

2.1 Concepts and Design Frameworks

A circular building is "a building that is developed, used and reused without unnecessary resource depletion, environmental pollution and ecosystem degradation. It is constructed in an economically responsible way and contributes to the well-being of people and the biosphere. Here and there, now and later. Technical elements are demountable and reusable at the end of their (extended) lifespan, and biological elements can also be brought back into the biological cycle" [3].

CBD supports the design of circular buildings. The Circular Buildings Toolkit [4] is one of the design frameworks available to support the design of circular buildings. It provides a set of objectives and targets to point out and assess circular buildings. This framework is different from others since it arranges design strategies along the design process from the design brief to the manufacturing and construction according to the RIBA plan of work [5] to support the design team and key stakeholders in the implementation of circular buildings. The RIBA Work Plan is a process model for building design, construction and use. This model does not include the recovery stage.

Within CBD, building reversibility is the ability of a building to be easily adaptable during its use to guarantee high transformation potential and to be easily disassembled at the end of its service life to guarantee high reuse potential. Building reversibility provides systems, components and materials with the capability to be adapted and dismantled without damaging surrounding parts to support the potential for transformation or reuse in other contexts [6]. Building reversibility is achieved by combining reuse, adaptability and disassembly strategies. Three dimensions of building reversibility are distinguished: (1) spatial reversibility to adapt spaces; (2) technical reversibility of systems to reconfigure/upgrade systems; (3) technical reversibility of elements to separate elements and materials [5]. The Reversible Building Protocol (Table 1) is a design framework developed to address building reversibility.

Spatial reversibility is defined as the capacity of a building space to accommodate different functions by allowing transformation from one use scenario to another without causing major demolition, reconstruction works, material loss and waste creation. Three design aspects impacting spatial reversibility were identified in the preliminary design stage: 1) *dimension* of the building block, block floor-to-floor height and façade opening, 2) *position* of the core and load-bearing elements and 3) *core capacity* to carry loads and provide space for services [7].

Technical reversibility is defined as the capacity of systems and elements to be adapted to accommodate change or to be disassembled for reuse by organizing them and defining the relationships between them in a way that will support adaptability, disassembly and reuse [7]. Three design strategies are identified to implement technical reversibility [6]:

- *Functional decomposition* and *functional independence*: definition of functional hierarchy and allocation of functions to separate physical elements.
- *Technical decomposition*: hierarchical arrangement of the physical elements, and hierarchical relations.
- *Physical decomposition*: interface definition between physical elements.

Table 1. Reversible Building Protocol [7].

Design stage	Design objectives	Design strategies
Preliminary design	Spatial reversibility	• Dimension • Position • Core capacity
	Technical reversibility of systems *by functional decomposition*	• Functional independence • Systematization and clustering
Definitive design	Technical reversibility of elements *by technical decomposition*	• Hierarchical relations between elements • Base elements specifications • Life cycle coordination in assembly/disassembly
Technical design	Technical reversibility of elements *by physical decomposition*	• Assembly sequences • Type of connection • Interface geometry

This study compared the Reversible Building Protocol [6] and the Circular Buildings Toolkit [2] to understand how building reversibility is addressed within CBD. The two design frameworks were aligned looking at the design process, design objectives for adaptability, disassembly and reuse, and related design strategies. The design process [5] consists of 5 phases: 1) strategic definition, 2) preparation & briefing, 3) concept design, 4) spatial coordination, and 5) technical design. In terms of strategies, based on the definition of building reversibility [6], design objectives and design strategies related to reuse, design for disassembly and design for adaptability were compared. The comparison is shown in Table 2.

This comparison showed that 1) building reversibility in all its dimensions is not yet fully supported in CBD; 2) building reversibility is not supported at all in the concept design of CBD; 3) spatial reversibility is supported only starting from the spatial coordination stage of the design process; 4) technical reversibility is supported only starting from the technical design stage of the design process; 5) late stages of the building life cycle (manufacturing, construction, use and recovery) are not supported at all in terms of building reversibility; 6) strategies for building reversibility could be embedded in the concept design and spatial coordination stages of the design process to advance CBD in the ability to address spatial and technical reversibility.

Table 2. Reversible Building Protocol vs. Circular Buildings Toolkit.

	Dimensions of reversibility	*Design objectives and strategies*	
		Reversible Building Protocol [6]	*Circular Buildings Toolkit* [4]
1	Building (spatial and technical) reversibility	–	*Refuse new construction* • Reuse, renovate or repurpose an existing asset
2	Spatial reversibility	–	*Increase building utilization* • Increase the multi-use potential of building spaces
	Technical reversibility of systems	–	–
3	Spatial reversibility	• Dimension • Position • Core capacity	–
	Technical reversibility of systems	*Functional decomposition* • Functional independence • Systematization & clustering	–
4	Spatial reversibility	–	*Increase building utilization* • Create the general physical conditions to enable multi-use implementation • Design for increased utilization of regularly "empty" spaces *Design for adaptability* • Choose architectural massing, structural grid and foundation layout compatible with future uses • Allow for changes in building use by designing the building envelope to allow for more than one use or modifications in window size and spacing • Make passive provision accounting for changes to MEP systems and provide a plant replacement strategy

(*continued*)

Table 2. (*continued*)

	Dimensions of reversibility	*Design objectives and strategies*	
		Reversible Building Protocol [6]	*Circular Buildings Toolkit* [4]
	Technical reversibility of elements	*Technical decomposition* • Hierarchical relations between elements • Base elements specifications • Life cycle coordination in assembly/ disassembly	–
5	Spatial reversibility	–	*Increase building utilization* • Design local building performance units for various space configurations and requirements • Make use of versatile/flexible/ movable internal walls for the space layout to support multi-use *Design for adaptability* • Develop and issue an Adaptability Manual document
	Technical reversibility of elements	*Physical decomposition:* • Assembly sequences • Type of connection • Interface geometry	*Design for disassembly* • Develop reversible connections between the structure elements • Allow access to reversible connections between structure and services • Develop and issue a Disassembly Manual Document

2.2 Design Tools

An exploration of existing design tools available to support building reversibility within CBD was performed. It aimed to support an early understanding of current trends and potential gaps. The exploration was limited to insights from existing research and the researcher's experiences. The following set of tools were identified: a) Regenerate [8], b) DGNB Conversion and deconstruction-friendly planning and DGNB Multi-use of areas [9], c) CBC-generator [10, 11], d) Reversible BIM within Digital Deconstruction (DDC) [12], and e) One Click LCA Building Circularity [13]. They were analyzed and compared in terms of building lifecycle and design process stages, design activities and dimensions of building reversibility (Table 3).

Table 3. Design tools comparison.

Tools	*Building life cycle phase*						*Design process phase*					*Design activity*				*Dimensions of reversibility*		
	1	*2*	*3*	*4*	*5*	*6*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*1*	*2*	*3*
a)	●	●								●	●	●			●	●		●
b)		●								●	●	●			●	●		●
c)		●	●		●				●	●	●			●	●		●	●
d)		●		●	●				●	●	●				●		●	●
e)		●								●	●				●			●

Building life cycle phases (adapted from [5]): 1. Strategic Definition & Briefing; 2. Design; 3. Manufacture; 4. Demolition & Construction; 5. Use & Refurbishment; 6. End-of-life.
Design process phases (adapted from [5]): 1. Strategic definition; 2. Briefing; 3. Concept design; 4. Spatial coordination; 5. Technical Design.
Design activities [14]: 1) briefing; 2) analysis; 3) generation; 4) evaluation.
Design dimensions of reversibility: 1. Spatial reversibility; 2. Technical reversibility of systems; 3. Technical reversibility of elements.

The comparison showed that 1) support is mainly focused on the design phase of the building life cycle process. Limited support is provided in the early stage (strategic definition and briefing) and late stages (manufacture; demolition and construction; use and refurbishment; end of life); 2) there are no or limited tools that support the early design phases (strategic definition, briefing, and concept design). Support is mainly provided in the late stages of the design process (spatial coordination and technical design); 3) most of the tools help in evaluation while briefing, analysis and generation are limited supported; 4) designers are mainly supported in the evaluation of solutions in terms of spatial or technical reversibility. Limited support is provided to generate solutions that implement spatial and/or technical reversibility; 5) there are no tools available to support all three dimensions of building reversibility.

3 Matrix-Based Product Modelling Methods

Matrix-based product modelling methods are engineering design methods used to facilitate the modelling of relations in complex systems. They are classified into three types [2]: 1) *Element-level matrixes* represent the relationships between the same types of elements/parts/components of a product or between elements of different types using a matrix; 2) *Product-level matrixes* map the relations between a set of product aspects and product alternatives; 3) *Matrix-based methodologies* use element-level and product-level matrixes to manage complex multidimensional problems systemically and coherently such as the development process or the interactions within products, processes and organizations.

3.1 Axiomatic Design and Design Structure Matrix

AD and DSM are two matrix-based product modelling methods increasingly being used for reversibility in complex systems through modelling relations since the concept design stage.

AD is a matrix-based methodology created by Suh [15, 16]. It provides a design framework with a systematic procedure and general principles to support designers through the design process to model, track decision-making and examine relationships between functional elements and physical components in a structured manner from early design stages. It has been applied to different areas, including non-engineering fields [17] and building design [18], in different stages from synthesis to the evaluation of the synthesized idea, and the selection of the best ideas from alternatives [15, 16]. AD process consists of mapping from problem to solution and from sub-problems to sub-solutions through consecutive design domains (customer, functional, physical, and process domains) and of decomposing hierarchically from general to specific to develop the design in finer levels of detail [15, 16].

DSM is an element-level matrix-based product-modeling method created by Steward [19]. DSM is a representation and analysis tool for system modelling in the design of products, processes, and organizations [20]. In the design of products, it is used for representing relationships and interfaces among components. A DSM process consists of decomposing the system into components, analyzing and quantifying interactions between components in terms of spatial, energy, information, and material, reporting information in a matrix; and grouping highly interactive components in modules [20].

In this study, AD and DSM are proposed to be combined (Fig. 1) to support CBD for building reversibility. AD-DSM can support modelling a building system in terms of functional and technical decomposition and define interactions between its components for physical integration to allow the system to be easily adapted during its lifetime and easily disassembled at the end of its service life for recovery, reuse, refurbishing, remanufacturing or recycling. Specifically, AD can support the implementation of spatial and technical reversibility in CBD. According to [21], this methodology can be applied to building design to implement both spatial and technical reversibility.

AD supports defining functional elements (FRs) and arranging them in physical components (DPs) by mapping FRs and corresponding DPs to implement functional independence. Then, through the zigzagging process, functional decomposition and technical decomposition are performed generating a hierarchy of functional elements, a hierarchy of physical components and hierarchical relations within them. However, through AD, only relations between FRs and DPs are identified for functional and technical decompositions while relations between components for physical integration are not supported.

DSM is proposed to support physical decomposition (and clustering) for building reversibility within CBD. By using a matrix, DSM represents the physical relationship between physical components and groups them into modules by considering the physical connection between components. Although DSM provides a method to model component interactions and group components into modules, it is difficult to generate a design concept by using DSM alone. Also, it assumes that the designer defines functional elements and related functional-uncoupled physical components implicitly.

AD-DSM has been already applied in disciplines such as mechanical engineering [22], product design and manufacturing [23], and construction process management [24] showing complementary benefits while it has not yet been applied to CBD. According to [21], AD can support the design process of analysis, synthesis, generation and evaluation of relationships between functional elements and physical components in a structured manner from early design stages by providing a procedural framework and design principles. DSM can support the modelling of relationships of physical components and group them in modules. So, AD is incapable of analyzing the physical component interactions, which is the great strength of DSM. DSM cannot support the design generation; whilst AD could cover this shortage.

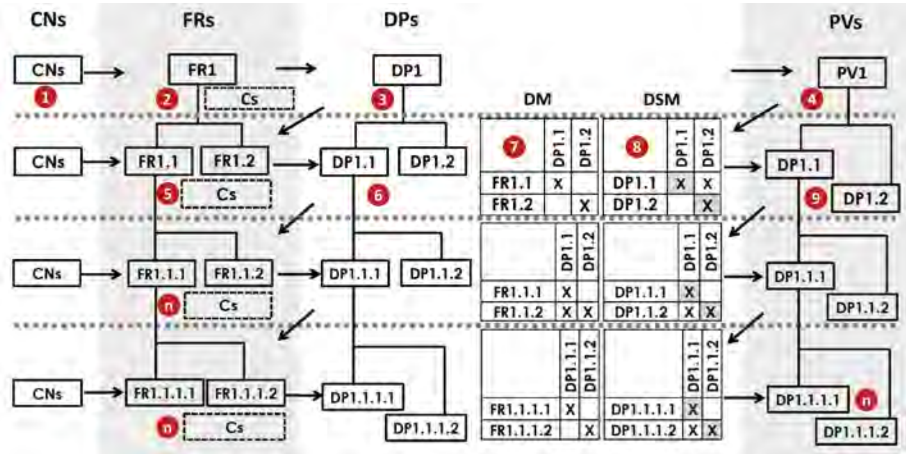

Fig. 1. AD-DSM framework (1. define customer needs (Cns); 2. define the top-level FRs; 3. define the top-level DPs; 4. define the top-level process variables (PVs); 5. decompose the top-level FRs into FRs at the lower levels; 6. define sub-solutions in terms of DPs at the lower levels; 7. check using the design matrix (DM); 8. define relations between DPs using the DSM and cluster DPs; 9. decompose the top-level PVs into PVs at the lower levels)

4 Design Propositions for Circular Building Design

The study defined the following propositions:

1. Within CBD, building reversibility is the ability of a building to be easily adapted during its use to guarantee high transformation potential and then to be easily disassembled at the end of its service life to guarantee high reuse potential of building systems, components and materials. Building reversibility is implemented through three dimensions of reversibility: spatial reversibility, technical reversibility of systems and technical reversibility of elements. However, the design of building reversibility in all its dimensions is not yet fully supported within CBD.

2. The design of building reversibility within CBD is supported by a few tools that mainly support the late design phases (spatial coordination and technical design) while the early phases (strategic definition, briefing, and concept design) are limitedly supported. Most of the tools help in the evaluation of solutions in terms of spatial or technical reversibility while briefing, analysis and generation of solutions to address building reversibility are limited supported. Moreover, no tools are available to support all three dimensions of building reversibility.
3. AD-DSM can support the design of building reversibility in its three dimensions in the early stages of CBD by facilitating functional decomposition, technical decomposition and physical integration. It can support modelling, combining and tracking decisions from the concept design for designing building systems that can be easily adapted during their lifetime and easily disassembled at the end of their service life for recovery. AD guides the designers through the design process to model, track decision-making and examine relationships between functional elements and physical components in a structured manner from early design stages. to implement spatial reversibility and technical reversibility of systems. DSM provides a method for modelling physical relationships among physical components and groups them into modules to implement technical reversibility of elements.

In conclusion, despite the role of building reversibility in CBD, the design of building reversibility is not yet fully supported, especially in the early design stages even if decisions made in the concept design have a strong impact on expected results. The study elaborated the proposition of combining AD and DSM to provide a framework and process in the concept design to model, check and track decision-making for building reversibility within CBD. Current limitations of the study in the literature review, comparative analysis, methodological explanations and lack of applications will be overcome in future research. Literature review, comparative analysis and methodological explanations will be further expanded to consolidate understanding. The theoretical proposition will be tested in the design of circular building components to demonstrate real-world applications while detecting challenges and limitations to assess effectiveness in supporting building reversibility within CBD.

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Development of a Circularity Assessment Tool with Local Stakeholders from Strasbourg

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Abstract. Our research focuses on the reutilization of construction materials and how we could foster growth in this sector. It deals with the specific case of the re-use sector around Strasbourg, France, providing a comprehensive overview of the local landscape. Indeed, the research was conducted in partnership with the School of Architecture of Strasbourg, the City of Strasbourg, and an engineering consultant called "BOMA" specialized in circular building. This project is supported by the "Campus des Métiers et des Qualifications Eco-construction et Efficacité Energétique Grand Est", the Grand Est Region, the "Région Académique Grand Est" and the "Banque des Territoires". To encourage innovative programs around circular economy, we gave particular attention to analysing feedbacks from pilot projects. In addition to the interview with key local stakeholders, a literature review focusing on assessment of circularity in buildings was carried out. Through a methodology developed in a separate scientific paper, we selected 10 key indicators adapted to the area to measure the circularity of a building, focusing mostly on social, environmental, and economical aspects of the project. Thanks to these indicators, a digital tool was developed to calculate the relevant data concerning the circularity of the project, creating analysed feedback of the construction. Five of those indicators have been implemented in this tool, although suggestions have been made to cover more topics. Moreover, in the future, there is the possibility for it to be transformed into a decision-making tool in order to boost the structuration of the re-use sector around Strasbourg.

Keywords: Construction · Re-use · Circular Economy · Strasbourg · Tool · Evaluation

1 Introduction

Until the beginning of the 20th century, reutilization of constructions material was a common practice. The high cost of extraction and transportation and transformation of raw material forced builders to give priority to the resources already present in town [1]. This organization of building materials has evolved through time, with new technologies, low cost of energy and higher labour cost.

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Nower days construction methods are facing several issues, one of them is the major amount of construction waste. In France, the construction industry is responsible for 46 million tons of waste, that represents 53% more than household waste [2].

In this context, the development of circular economy and specifically the re-use of construction materials is a major lever to reduce construction waste and promote existing materials. The European commission defines re-use as "*any operation by which products or components that are not waste are used again for the same purpose for which they were conceived*." [3] The Belgian research group [1] highlighted three main arguments for the practice of re-use:

- reduction of the environmental impact, the effects of each step of the "extraction of raw materials" and "production of the product";
- creation of local and social employments by also bringing value to existing professions such as building wreckers who's missions will evolve into the sustainable deconstruction and re-use of materials;
- preservation of the architectural heritage.

This practice with several positive impacts is re-emerging, thanks to local stakeholders and national regulations. The creation in 2022 of the Professional Union for Reuse in the Construction Industry in France, is an example of the national structuration. However, the structuring is taking place in different ways across the country.

The Strasbourg case study is an interesting example given that it is a medium sized town, at the centre of the European landscape, willing to structure and develop the re-use sector in the area. In the following paper, we will focus on the levers used by those involved in the re-use sector in and around the Strasbourg area and the main obstacles they face. In response to this state of the art, we will describe the analysis tool developed as part of this study.

This research was conducted in partnership with the Research Unit of the Architecture School of Strasbourg, the "Eurométropole de Strasbourg" and BOMA, an engineering consultancy in circular economy in the building sector. This partnership has firmly rooted the study at a local and regional scale and enabled us to identify the stakeholders' main needs. One of these needs is to receive feedbacks from pilot projects in order to collect data and give the project owner the opportunity to value its investment. Moreover, in France as in Spain and in Italy the project owner must cover the 10 years period after delivery of the project with a decennial liability, the circularity assessment is also a way to reassure same building stakeholders that the practice is doable and safe. In this context, we worked on a digital tool that analyses feedbacks from pilot projects.

The recent thesis from Ambroise Lachat [3] provided a solid foundation for the research conducted here. His study cited the comprehensive article by Nuñez-Cacho et al. [4] which also describes a method to identify the key indicators to measure circularity in a project. Finally, the paper published in 2023 from S. Clavier et al. [5] studies the re-use rate by using the Material Flow Analysis method. This research underlines the necessity and interest for the topic today.

2 State of Art

The structuration of the re-use sector in France is heterogeneous and depends on different factors. In this study, we focus on the Strasbourg situation, a city located on the border with Germany and side by side with the Rhine River. This location makes it a European city which can participate to European program such as the INTERREG finance program, FEDER or LIFE.

The re-use sector today has a strong sense of community and a great willingness to share experience. In the context of the Waste2Build project financed by the European program LIFE, the French city of Toulouse received funding to develop the re-use sector. LIFE project implies the sharing of knowledge with other European territories.

Moreover, we noticed that the re-use sector structuration will also operate thanks to the support of public policies and territorial collectivities. Examples of other territories show that the first lever to accelerate the development of a re-use sector is to implement effective public policies. In the territory of Plaine Commune in the Paris Region, the stakeholders signed a charter, with numerous goals to support the re-use sector. National measures can also be an effective lever. Indeed, since the 1st of July 2023, for most demolitions, the project owner must do a resource diagnostic in order to identify the reusable building materials. This measure provides considerable leverage for identifying possible local resources.

Finally, through this research and interviews with local stakeholders, we were able to point out the urgent need to share knowledge. Most consultancies specializing in circular building offer educational programs for companies or schools.

There is a need to gather knowledge and analyse pilot projects, so that the project owner can communicate and share solutions that function. In the following article, we will try to find a solution that fulfils this need.

Concerning the research sector, we noticed a growing interest for the development of circularity in buildings. Marie de Guillebon [6] in her thesis in 2019 worked on experimental construction projects using re-used materials and on the value of the materials. Another key research is the work of the Belgium research group which includes the catholic University of Louvain, the Vrije Universiteit Brussel, the CSTC and Rotor [1], on the case study of Brussel, which took place from 2015 to 2017.

Concerning the assessment of circularity, the literature review from Hossain & Ng [7] shows that there is a global interest for this subject. The authors highlight the importance of considering circular economy in LCA analysis: *"Although some important research gaps were highlighted from different perspectives of building assessment, none of those studies has considered integrating a circular economy (CE) with LCA for more sustainable building construction."*

The focus of the state of the art was made on the different research working on the circularity assessment. First, the study from Nuñez-Cacho et al. [4] suggests a method to select circularity indicators using a literature review. This method has been used to define the indicators adapted to the circularity assessment in Strasbourg and adapted to the maturity of the local sector.

Lachat [3] in his thesis also pointed out this urge to include CE in the building assessment, he adds that we can't study a perfect cycle of a product but multiple ones, since through reusing process, some of the values of the materials are lost. This study focuses on the evolution of circularity assessment through time, questioning the method exposed by Zhang et al. [8]. In addition to those studies, a work has been recently published on reusability [5], the study program focused on a methodology to calculate the re-use rate of a material, their first case study is about the re-use rate of bricks.

The Scientific and Technical Center for Building, CSTB, updated in 2018 their research program for 2025 through four strategical guidelines. One of these guidelines is "the circular economy and resources for construction" and CSTB organized in July 2023 a research day on this topic, presenting their ongoing research.

The need to collect and analyse feedback is more and more present and we notice a lack of tools on the assessment of the circularity of an entire building.

3 Methodology – Development of a Circularity Assessment Tool

The development of a circularity assessment tool is essential for the projects in and around Strasbourg, through several aspects:

- Raising awareness about circular economy (CE) in the construction sector;
- Helping to define the key indicators of circular economy;
- Collecting feedback and learning collectively from them;
- Helping the development of a CE certification.

The methodology used for the development of an assessment tool was inspired by the methodology called the e-delphi technique which can be found in the study from Nuñez-Cacho et al. [4]. Using literature review and report analysis, they identify 234 indicators that can fit with the assessment of circularity. By eliminating duplicates and interviewing stakeholders, they manage to reduce to a seven indicators list.

A similar methodology was used to define the adapted indicators for the Strasbourg area, going from 62 to 10 indicators through two different scales (see Fig. 1 and Fig. 2). The first list of indicators was completed thanks to multiple resources such as interviews with local stakeholders, indicators from other calculation tools and research work.

This list was divided into two distinct scales: the building level and the sector level. This partition serves to shed light on a broader perspective on circularity, including both micro and macro viewpoints. Then we erased the duplicates and gathered the indicators into 6 categories described in the following Table 1 and Table 2.

Table 1. Categories selected on a re-use sector scale.

Sector scale		
Category	Indicator	Description
Skill valorization	Creation of local job	Creation of reinsertion jobs
	Development of one or several re-use platforms	Systematizing the use of reusable components will help to encourage the emergence of new initiatives
Valorisation avec the projects	Pilot project	Exemplary projects provide inspiration and show the way to other projects

Table 2. Categories selected on a building scale.

Building scale		
Category	Indicator	Description
Environmental impact	CO_2 emissions	CO_2 emissions saved thanks to the integration of re-used materials in a building
	Raw material management	Mass of building raw material saved
Economic impact	Economic impact	Economic impact through the implementation of reuse materials
Social impact	Social awareness	Awareness/information/training of construction stakeholders and development of common knowledge
Future resources management	Reusability and recyclability	Planning the change of usage or the end of the life of the building

Eight of those ten indicators have been implemented in the digital tool using two specific methods.

Firstly, the qualitative indicators (Social impact, Skill valorisation, Valorisation of the project), those which can't be calculated have been implemented in the Part 1 of the tool.

The weighting given to each criterion in Table 3, was discussed with a CE project chief from the "Relais 2D"[1]. They are adapted to the needs of the sector, valuing the

[1] Organization in charge of the inclusion of social and environmental clause in public market of Strasbourg.

Table 3. Social impact assessment of the project.

Building scale	*Selected*	*Calculated*
Awareness for the re-use sector		
Project owner	No action/Informing/Awareness/Training	0/1/2/3
Project manager	No action/Informing/Awareness/Training	0/1/2/3
Building workers	No action/Informing/Awareness/Training	0/1/2/3
Users	No action/Informing/Awareness/Training	0/1/2/3
Creation of reintegration jobs	No/Yes	0/3
Creation of an apprenticeship	No/Yes	0/3
Sector scale	*Selected*	*Calculated*
Support for the development of a physical or digital re-use platform	Blank = no help /*/**/***	0/2/3/4
Exemplary construction including re-use technology *Here, we call an exemplary re-use project, an innovative project, that is valued by a specific communication (visits, presentation, public reports, etc.)*	No/Yes	0/2

most ambition projects. Nevertheless, this weighting is still experimental and requires to be updated in the following years.

Secondly, we focused on the quantitative indicators such as carbon footprint, raw material resources management, economic impact, and future resource management.

- In the French legislation, for new constructions, the carbon footprint of re-used equipment or material is counted as 0 CO2-equivalent (CO2e), it is a political decision to support circular economy in the country. The tool suggests a first calculation of the overall carbon savings thanks to the integration of re-used products with this calculation method. A second calculation is suggested, the "real" carbon footprint of the material. For this calculation, we used the method developed by Cycle Up, an engineering consultancy in circular economy in the building sector, and the agency Riverse.
- Concerning the raw material resources management, we calculated the weight of trash saved thanks to the re-use operation using the Eq. (1).

$$w_{tot} = \sum_{i}^{n} w_{unit\ product\ i} * q_i \tag{1}$$

w_{tot}: *total weight of trash saved*
$w_{unit\ product\ i}$: *weight per unit of the material i, using the data based of the tool*
q_i: *quantity of the product i*

n: quantity of different re − used products

- The economic analysis consists only for now, on a comparison between the new and re-used product price, which has been led. A deeper study could be done in order to get a better view of the economic impact of the integration of reused materials.
- Finally, the evaluation of the future resources management hasn't been implemented yet so far as this notion is still uneasy to measure. However, it is a crucial information to collect for the reusability in the future of integrated products. Incoming French research studies are working on the calculation of the reusability rate of some products, but no general data base has yet been provided.

4 Methods Application - Case Study: Pilot Project Around Strasbourg

4.1 Description of the Project

This case study was focused on a technical unit in the town of Schirmeck owned by the "Collectivité Européenne d'Alsace". The public project owner wanted to include re-used products in order to reduce the environmental impact of the project. The technical unit includes 3 main buildings, a shelter for road salt, a garage and an administrative building. In the following paper we will focus on this last building, which included the largest amount of reused products.

Fig. 1. Picture of the finished the administrative building of Schirmeck (left), pictures of the re-used material (right).

Most re-used materials are originally from interior construction so far, as they are easier to be insured by insurance companies. In the new building, many materials have been reused (see Fig. 1) and we will now see what results we get using the methodology explained above.

4.2 Project Analysis

To deconstruct and store the re-used materials, the Collectivité Européene d'Alsace called a social organization helping people to find jobs after long periods without any and having been through difficult situations. The project was communicated over the media thanks to a regional news program. It achieved 46% of the social goals defined above.

Concerning the carbon indicator, we chose to compare the impact of a new material to the impact of a re-used one, using the method developed by Cycle up (see Fig. 2).

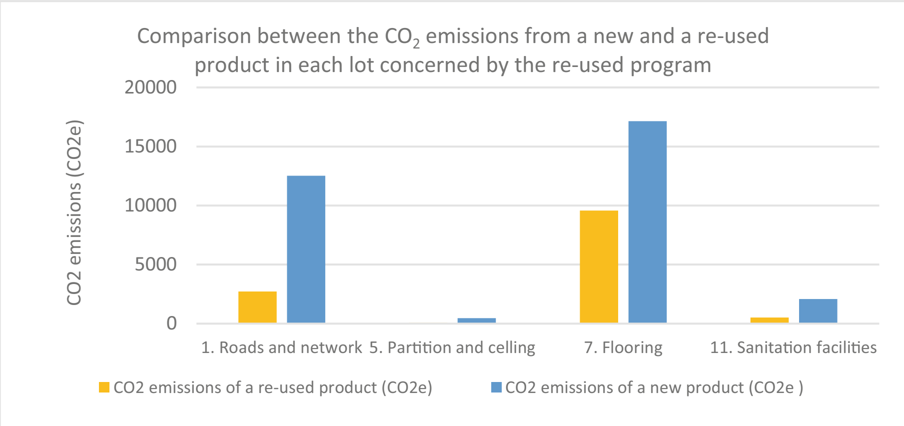

Fig. 2. Carbone emissions with both scenarios, re-used and new products.

We can clearly acknowledge the positive impact of re-used materials in this context. Moreover, the French legislation considers the carbon impact of a re-used equipment or material to be 0 CO2e, an incentive measure that digs the gap between a new and a second-hand construction product. Concerning the economic impact, the following graph has been generated (see Fig. 3).

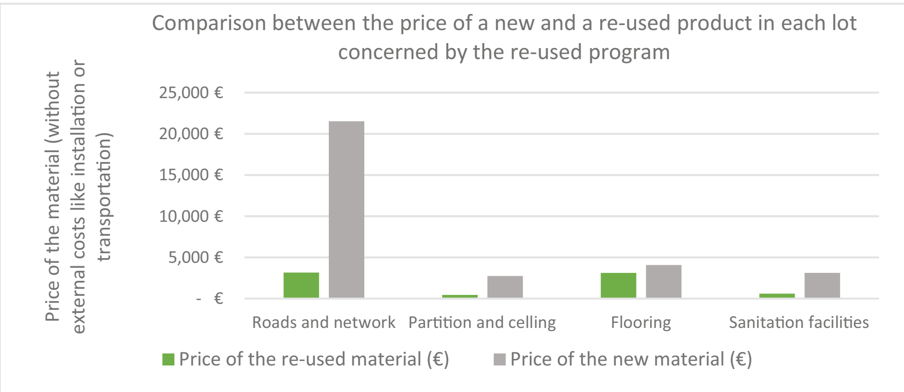

Fig. 3. Carbone emissions calculated with two different methods.

In practice, additional costs are generated on the cost of the material (intellectual cost connected to the specified engineering office for example). The study provides a flow chart of these costs to be considered in order to define the overall price of the product.

Further research needs to take place to define this exact price. Nevertheless, this shows the economic potential of reused products and the importance of expanding the practice to minimize external costs.

5 Conclusion

A tool for analysing the circularity of projects has been developed to support the emergence of the re-use sector in the "Eurométropole de Strasbourg". The creation of this software meets the need to collect the best local practices and to study the overall impact of a project. Indeed, this study shows the necessity of covering a range of factors rather than focusing only on the carbon footprint of each material or the energy efficiency of the building. Following this guideline, many questions arise concerning the scope of the assessment, the criteria to be considered and the calculation methods to be adopted. Bearing in mind that the development period has taken place over less than 6 months, the main goal of the study was to propose the start of a global analysis of the circularity of a project. This tool also provides a proposition to the "Eurométropole de Strasbourg" in its role as project owner, offering tools for feedback, analysing possible modifications in the circularity of their project and, why not, introducing goals into government procedures.

To make this tool fully operational, two main areas of development must be pursued. First, there is a need to keep testing the software with further case studies. These tests will assist in the development of a fair social evaluation and could help refine assessments for other indicators. Secondly, the economic and future resources management indicators could be improved to better match the expectations of local stakeholders.

However, we have observed that conducting a comprehensive study of the circularity of a project is a complex task that raises many issues. Nevertheless, we can agree on the low rate of reused construction materials in the overall building. The difficulty in reusing more materials may also stem from the design of the building itself, which, in most cases, rarely considers the building's end-of-life. Furthermore, a design that is too rigid does not allow the building to be repurposed, or its materials to be reused. These considerations for future re-use needs to seriously begin now. The "Eurométropole de Strasbourg", as project owner, recently included clauses in their procedures stipulating that the fact that the building will be dismantled in the long run should be considered from the moment it is built - an innovative initiative coming the local authority.

The current limitations for the re-use sector to be developed on a more global scale are the lack of operational and digital tools, and the question of whether circular economy principles should be integrated into current design tools, such as BIM6D and AI methods. This would imply the widespread acceptance of such specialized efficient tools among architectural agencies, which is not currently the case. Moreover, this technology currently still requires a great deal of energy, which can contradict in certain cases the main goal of reducing the impact of construction on our resources. The key may lie in the implementation of several different solutions, from the data collecting to the circular design using adapted tools.

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Water Efficiency, Consumption and Management in Environmental Performance Assessment Methods for Existing Buildings in Use

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Abstract. One of the major motivations behind the effort for the transition from linear models to circular ones in the building sector is related to the need for the minimization of resources depletion. Water holds a prominent position among those resources. The building sector is responsible for appreciable water consumption and, hence, represents an important field for improvements. While in the case of new buildings several options are available for the relevant systems and strategies, when existing buildings are considered, the limitations are multiplied in the context of decisions already made and materialized. However, the existing building stock is a massive contributor to the total impact of the built environment and must be considered as well. In this work, three buildings' environmental performance assessment methods (BREEAM, DGNB, LEED) and, specifically, their versions for existing buildings in use (residential and non-residential), are examined regarding the way water-related parameters are implemented in the evaluation that they perform. The factors reviewed are those associated with water regarded as a resource (water consumption, (re-)use of rainwater, management issues etc.) and not the ones referring to flood risks and to energy demand (hot water). The analysis' main focus lies in the criteria used by each method, the main strategies highlighted as advantageous, and issues related to the integration of those evaluation axes into each system. Initially, main features of the three methods are presented (assessment structure, scoring process, etc.). Among others, differences and similarities in the adopted approaches (three evaluation methods, various building uses) are highlighted and discussed.

Keywords: Water Use · Water Management · Buildings' Environmental Performance Assessment Methods · Existing Buildings in Use

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1 Introduction

Resource depletion is one of the major problems that dictate the transition towards production and development models based on environmentally friendly strategies. Among the promising approaches aiming towards the conservation of resources, circular economy is listed. Water, being indispensable for industrial processes, in fact for life itself, is included in the resources that are endangered by the advancing climate change. The implementation of strategies in the most aggravating sectors of human activity, aiming at the deceleration and reversal of these developments, is crucial. The building sector is a significant contributor to the consumption of water, representing at the same time an important field for improvements. Not surprisingly, water is taken into consideration in all of the methods for buildings' sustainability assessment. Reviews of water-related parameters' integration in such systems can be found in studies focusing solely on this issue (e.g., [1]) or addressing it in a broader context (e.g., [2]).

The existing building stock, created in the course of several decades and representing different priorities and philosophies, is a major actor in the built environment's sustainability. Hence, the rating of existing buildings' environmental performance is very important. In this work, well-known sustainability assessment methods (BREEAM, DGNB, LEED) for existing buildings in use are critically reviewed regarding the integration of factors associated with water into their assessment structure and philosophy. Aiming at a wider scope of analysis, the most recent internationally applicable versions of these methods, addressing both residential and non-residential buildings, are examined. In this context, parameters associated with water as a used resource are included in the study (i.e. water pollution, flood risk, hot water-energy wise, etc., are not addressed). Issues referring to the relevant criteria applied in each method (content, basis of calculations, section and level of the assessment structure into which they are included, etc.) are investigated and systematically presented. The main thematic areas examined are identified. This analysis is preceded by the presentation of basic features of the examined schemes ("structural" issues, assessment processes, ranking categories, etc.), so that a solid framework is formed for the water-specific elements to be presented. It is noted that, within the present and the following text, the terms "method", "system" and "scheme" are used interchangeably; the same applies also for i) the terms "residential" and "domestic" buildings/uses, and ii) the terms "environmental performance assessment" and "sustainability assessment". The presented information regarding the issues explored in this study is derived mainly from the examined systems' technical manuals/guides. This work results in the presentation of the approach adopted by each scheme with regard to the examined issues and in the subsequent detection of similarities and differences among them.

2 Description of the Examined Methods' Basic Characteristics

2.1 BREEAM In-use

BREEAM (Building Research Establishment's Environmental Assessment Method) was initially published in 1990, being, therefore, the first system to be introduced for the assessment of built environment's sustainability. Through years and a continuous development process under the responsibility of BRE (Building Research Establishment), the method has expanded to address a variety of building uses at various stages of their lifecycles, as well as built environment's larger scales. Among the constantly evolving versions of the method, which apply for different evaluation objects and or in varying geographical areas, the ones referring to the buildings in use are listed. The first version addressing this stage of buildings' lifecycles was introduced in 2009 [3].

In this work, the most recent, internationally applicable versions for the assessment of in-use residential and non-residential buildings' environmental performance are examined ([4] and [5], respectively). Student accommodation, hotels, care homes and hostels are classified as non-domestic buildings. The structure and the evaluation process of those two schemes is similar. Specifically, the evaluation process in both cases is divided into two parts: i) asset performance (referring to the actual performance of the examined asset)-Part 1 and ii) management performance (addressing the management processes)-Part 2; Parts 1 and 2 can be employed independently and receive separate scores. In each one of the two Parts, a plethora of parameters are examined. Those parameters are organised into major *environmental sections*. In case of the asset's performance evaluation Parts, in both schemes [4, 5], those *sections* are: i) "Health and Well-being", ii) "Energy", iii) "Transport", iv) "Water", v) "Resources", vi) "Resilience", vii) "Land Use and Ecology", viii) "Pollution". In the context of the management performance assessment Part, the aforementioned set of *environmental sections*, with "Transport" being excluded, is accompanied by an eighth one entitled "Management". In all cases (both Parts, both schemes), an additional *environmental section* ("Exemplary") exists. With the exception of the latter *section*, all the others include *assessment issues*. In the context of each one of the *assessment issues*, a specified number of credits is available. Those credits (or some of them) are awarded to the assessed object depending on its performance regarding the evaluation criteria accompanying each *issue*. The ratio of the awarded by the available credits for each major *environmental section* is multiplied by its relative weighting, and the sum of those products, along with the contribution from the "Exemplary" *section*, provide the building's score (in [%]). This score determines the classification of the building into one of the ranking categories defined by the method (acceptable, pass, good, very good, excellent, outstanding). The available credits in the "Exemplary" *section* are awarded based on the achievement of exceptional performance in the context of specific *issues*, within which this possibility is provided. The *assessment issues* themselves (i.e. the level of the method's structure where the evaluation occurs) are structured based on a question accompanied by a number (variable among the different cases) of answers, each one corresponding to the awarding of a part of the available credits in this *issue*. The selection of each answer presupposes the fulfillment of specific requirements and conditions [4, 5]. Another component of the assessment process is the fact that, for the achievement of any level of ranking/certification, some minimum standards must be met (apart from the final score itself). Very few of those standards are prerequisite for all rankings and only for Parts 2 of the assessments.

While the general assessment processes and structures in the two schemes (residential and non-residential uses) have the same spine, some differences between them regarding individual factors can be identified. For example, the relative weights of the same *environmental sections* differ not only between Part 1 and Part 2 within one scheme (which is expected), but also between the respective Parts of the two schemes. In all cases, the sum of the relative weights of the *environmental sections*, excluding the “Exemplary” *section*, equals 100%. Another central difference between the two schemes lies in the available credits’ number within each *environmental section.*

2.2 DGNB System for Buildings In Use

Developed by the DGNB (German Sustainable Building Council), the homonymous system for the built environment’s sustainability assessment emerged in 2008 [6]. Its first version addressed new buildings of specific uses. Currently, versions of the method for many building uses, referring to various stages of their life cycle, and also to the bigger-than-the-building scales of the built environment, are available. The first DGNB scheme for the assessment of the sustainability of buildings in use was launched in 2006. Its most recent version, published in 2020 [7] and having an international scope of application, is the one analysed in this study.

This scheme applies both for residential and non-residential building uses [7]. Three major *topics* are defined in the system: i) “Environmental Quality”, ii) “Economic Quality”, iii) “Sociocultural and Functional Quality”. Each *topic* contains three *assessment criteria*, each one of which is accompanied by its relative weighting that outlines the *criterion’s* contribution to the building’s total score. The relative weights of the *assessment criteria* comprised in each *topic* sum up to the relative weight of the *topic* itself (“Environmental Quality”: 40%, “Economic Quality”: 30%, “Sociocultural and Functional Quality”: 30%). The assessment takes place at the *criteria* level. The available in the context of each *criterion* points are awarded –all or some of them– depending on the performance of the building in relation to a set of indicators; each indicator is accompanied by a number of available evaluation points and a set of requirements/conditions, the fulfillment of which determines how many of the aforementioned points are achieved. Generally, in each *criterion*’s context, 100 evaluation points can be achieved. In some cases, it is possible for the building to “achieve” more than 100 evaluation points but only up to 100 can be credited; there are some *criteria* in the context of which bonus points are available (increasing the upper limit of the possible-to-be-awarded ones). The awarded evaluation points in each *criterion* and *topic*, in combination with the respective relative weightings, are the basis for the derivation of the building’s total score, which is expressed as a percentage and leads to the building’s classification into one of the four performance ranks (bronze, silver, gold, platinum). In the examined scheme there are no *criteria* with minimum, prerequisite for the assessment, requirements (“knock-out criteria” [7, p. 15]).

An important feature of the assessments conducted with the examined system is the employment of the “continuous improvement” approach [7] for five out of the totally nine *assessment criteria* included in the method’s structure. This approach essentially consists of four steps (plan-do-check-act) and employs an iterative process. In those *criteria*, the evaluation of the actual performance and of the management-specific aspects takes place separately (two parts), with the four steps process belonging to the management assessment part. The sum of the available evaluation points in those parts (performance & management) within each *criterion* that comprises them, equals the respective sum of a “typical” *criterion*; in all *criteria* including those two parts, bonus points are also available.

2.3 LEED Operations and Maintenance

LEED (Leadership in Energy and Environmental Design) was initially launched in 1998 by the U.S. Green Building Council, and quickly developed far beyond the scope and possibilities of its pilot version. Currently it represents a major part of the built environment's sustainability assessment systems application worldwide. Having been continuously evolving to include more building types and uses, as well as neighborhoods and cities, it can currently be implemented for a wide variety of assessment items. The scheme for the evaluation of the environmental performance of existing buildings in use was released as early as in 2004 [8]. It has since been regularly revised along with the whole LEED method; currently, two versions are applicable (i.e. LEED for Operations and Maintenance v.4 [9] and LEED Operations and Maintenance v.4.1 [10]), with LEED v.5 being on the way. In this work, the most recent applicable version, revised in 2023 (beta version) [10], is examined. It addresses non-residential and residential buildings and provides the possibility for interiors- and existing buildings assessments. The present analysis focuses on the latter one.

The evaluation method in this scheme is structured on the basis of seven *environmental categories*, into which all the examined parameters are classified [10]: i) "Location and Transportation", ii) "Sustainable Sites", iii) "Water Efficiency", iv) "Energy and Atmosphere", v) "Materials and Resources", vi) "Indoor Environmental Quality" and vii) "Innovation". Each one of those sections includes *criteria*, which are of three types: i) *criteria* including conditions, the compliance with which is required (no points are obtained), ii) *criteria*, a number of the available points in the context of which is required to be achieved (and or some requirements must be met), and the rest of them may or may not be awarded, and iii) *criteria* without any mandatory items, with the available corresponding points being achieved by the building depending on the degree of fulfillment of the listed in those *criteria* conditions. The available points vary among the *criteria*, and, hence, among the *environmental categories*; their total number in the scheme is 100. The building's performance is reflected in the sum of the obtained points. Based on this score, the building's final ranking is derived (certified, silver, gold, platinum).

3 Water in the Examined Methods

3.1 General Considerations

As expected, the consumption and management of water as a resource represents an indispensable part of the assessments performed by the three examined methods. The related aspects are mainly classified in one major category/section of each system, with certain individual factors being included in the scheme's other major section(s).

In the case of BREEAM In-use, the central *environmental section* for the analysis of the themes examined in this work is "Water". Some individual factors regarding managerial processes are included in the "Management" *environmental section*; of course, they are relevant only for Part 2 of the assessment. The latter individual parameters are related to a) the existence of a user guide aiding the building occupants in applying efficient strategies with regard to, among others, water, b) the existence of improvement targets for various issues, including water, and c) the implementation of green lease agreements –applicable only for non-domestic buildings– promoting the consideration of more efficient practices. The relative weighting of "Water" *environmental section* is 9% and 8,5% for Parts 1 and 2, respectively, when residential buildings are concerned. The respective relative weights in the scheme addressing other building uses are 11% (Part 1) and 9% (Part 2). Parts 1 and 2 of "Water" *section* contain 10 (9 applicable for residential buildings) and 4 *assessment issues*, respectively.

In the case of DGNB System for Buildings In Use, the parameters associated with water use, efficiency and management are included, in their vast majority, in the "Water" *assessment criterion,* which belongs to the "Environmental Quality" *topic*. References to the reduction of water consumption can also be found in two *criteria* belonging to the "Economic Quality" *topic*. These cases regard mainly the operations cost (a closed water cycle offers bonus points) and the procurement and operations processes (incl. a guideline referring also to water use for cleaning). "Water" *assessment criterion* accounts for a share of 5% of the final score (its weighting represents the1/8 of "Environmental Quality" *topic's* relative weight).

Finally, the *environmental category* "Water Efficiency" of the examined version of LEED is the one that includes most of the issues addressed in this study. Only the management of rainwater is examined within another *environmental category* ("Sustainable Sites"). "Water Efficiency" consists of only one *criterion*, the compliance with the "requirements" of which is a prerequisite for the assessment; the fulfillment of other conditions included in it leads to the obtainment of more points. Specifically, 15 points can be obtained through the evaluation of "Water Efficiency" (out of the total of 100 ones available in the scheme); the achievement of 6 of them is a prerequisite for the assessment.

The study of the examined assessment methods led to the observation that the majority of the assessed parameters that are related to the issues investigated in this work can be organized into four main thematic areas: i) monitoring, ii) total water consumption (including drinking water and other water resources), iii) measures for the optimization of use and the minimization of consumption of water, and iv) reuse of greywater, rainwater and other types of "reclaimed" water. These are the main axes of the following analysis of each method's approach to the assessment of the building's performance aspects related to water use, efficiency and management. Some points referring to the features of each evaluation method are further commented on.

3.2 BREEAM In-use

In Table 1, information regarding the assessment of the 4 main thematic areas in the structure and context of BREEAM In-use is presented (residential and non-residential buildings), based on the contents of the respective technical manuals [4, 5]. Data related to the integration of the relevant aspects' assessment in the method's structure is presented in the second column of this table; the third column includes information on the parameters that are actually evaluated. Table 1 has been formulated on the basis of the contents of "Water" *section* for both residential and non-residential buildings [4, 5]. The differences between these two schemes are not presented in detail in Table 1, which includes information that describe the assessment's main components.

Table 1. Examination of water use, efficiency and management in BREEAM In-use ("Water" *environmental section*)

Thematic area	Inclusion in the method's structure	Main aspects assessed and examined
Monitoring	Examined within an *assessment issue*, belonging to Part 1. Minimum standard for all rankings apart from the lowest 2 ones. In its context, a credit for "exemplary" performance can be awarded (non-domestic buildings).	Installation of water supply meters able to provide immediate data and connect to a Building Management Software. For non-residential uses, installation of sub-meters for major water demand contributors. Metering water consumption at various levels (site, building, home-where applicable); for site-level: all types of water used (utility, rainwater, etc.) must be metered.
Total water consumption	Consumption of utility supplied water: examined within *an assessment issue*, belonging to Part 2. Consumption of recycled water: examined within an *assessment issue* in Part 2.	With regard to utility supplied water: reporting the annual consumption [m^3]. With regard to recycled water: annual consumption [m^3] from other sources (rainwater, blackwater and greywater) in order for the percentage of the total water consumption served by it to be evaluated.
Measures for consumption/use minimization/ optimization	Examined in 8 *assessment issues* of Part 1 (5 of those *issues* address water efficient equipment).	Efficiency of equipment (toilets, urinals-if applicable, showers, basins, appliances), assessed in item-specific terms (l/min, etc.). Existence of: a water leak detection system with specified abilities; appropriate controls for leak prevention-where applicable; isolation valves (fixtures, etc.).
Reuse of reclaimed water (greywater, rain water etc.)	Its consumption is examined within an *assessment issue*, belonging to Part 2 Its monitoring is also dealt with in case of metering at the site level (Part 1).	With regard to consumption: see "Total consumption" thematic area. With regard to metering at site level: see "Monitoring" thematic area.

Other parameters appearing in the context of "Water" *environmental section* (not included in Table 1) are the encouragement of reporting the collected data (via an *assessment criterion* in Part 2) and the adoption of strategies targeting refurbishments and maintenance schedules and processes that enhance water efficiency (again, via an *assessment criterion* in Part 2). As mentioned in Sect. 3.1, also some factors mainly related to management are examined in the homonymous *environmental section.*

An interesting observation lies in the detailed evaluation of water efficient equipment. The method does not just encourage such equipment items' application in general terms and or reward the resulting water consumption reduction, but it evaluates the performance of each relative asset (toilets, showers, etc.). Indicatively, it is noted that in the case of non-residential buildings, the related criteria account for about 69% of the 38 available credits within the "Water Efficiency" *environmental section* (in the context of Part 1-asset performance).

3.3 DGNB System for Buildings In Use

Table 2, structured in the same way as Table 1, outlines basic elements of the assessment approach within the system's "Water" *assessment criterion*, based on [7].

According to [7], the target for drinking water consumption can be set on the basis of the values calculated for water demand in the respective *criterion* in DGNB System for New Buildings. In this calculation several factors are considered (demand and waste by users, parameters related to rainwater, building use, etc.).

The step "check" of the continuous improvement process is not included in Table 2 in its entirety. It comprises an additional indicator related to the analysis of data acquired through the monitoring process; this indicator evaluates whether and how (quantitatively/qualitatively) the data is analysed, for further assessments to take place. This indicator is highlighted here (outside Table 2) as a distinct, well defined intermediate process within the continuous improvement concept.

Another issue that can be highlighted is the fact that the calculation of water exploitation index or baseline water stress indicator (country-specific), depending on whether the assessed building is situated in Europe or elsewhere, is awarded by the system. It can be said that those indices reflect, in general terms, water scarcity conditions. This approach indicates an effort towards the consideration of the actual conditions prevailing. Furthermore, the fact that the target value determination can be decided upon on a comparative basis (sets of similar/comparable buildings, consideration of innovative buildings) enhances the employed approach's relativity component.

3.4 LEED Operations and Maintenance

Analogously to Tables 1–2, Table 3 is formulated for the examined version of LEED; the information listed in this table is based on the contents and the structure of "Water Efficiency" *environmental category*, as presented in [10].

The water performance score, which forms the basis for the examination of the total water use, is calculated considering data on the total annual consumption, the gross floor area, the occupancy and the operating hours; the daily consumption per occupant and per floor area are derived and used as inputs. The calculated score reflects the performance of the assessed building relatively to the one of "comparable high-performing buildings" [10, p. 29], i.e. relativity-based considerations are explicitly referred to.

Table 2. Examination of water use, efficiency and management in DGNB Buildings In Use ("Water" *assessment criterion*)

Thematic area	Inclusion in the method's structure	Main aspects assessed and examined
Monitoring	Examined in the management assessment part, within the 2nd step of the continuous improvement strategy ("do").	Availability of water consumption data and way of collecting it (utility invoices-annual basis; monthly readings of water meter and invoices; digital monitoring on a continuous basis and invoices).
Total water consumption	Dealt with in the management assessment part, within the 1st step of the continuous improvement strategy ("plan"), and in the performance assessment part, within the sole indicator contained in it.	Within the "plan" step: Determination of a target value for drinking water consumption and basis of determination (internally; based on a set of similar buildings; based on an innovative - in technical terms– building). Identification of the area's water exploitation index or baseline water stress indicator. Within the performance assessment: check of whether the target value was achieved.
Measures for consumption/use minimization/ optimization	Dealt with in the management assessment part, within the 3rd step of the continuous improvement strategy ("check"), and in its 4th step ("act").	Within the "check" step: Check of whether and to which degree improvement measures already agreed on have been implemented. Within the "act" step: Taking operations improvement measures and way of deciding them (unless the values agreed on are met).
Reuse of reclaimed water (greywater, rainwater etc.)	Addressed in the management assessment part within the 4th step ("act") of the continuous improvement strategy, and is the core of the circular economy bonus available in the *criterion.*	Within the "act" step: see "Total consumption" thematic area. Within the circular economy bonus: Bonus points are available if a closed water cycle is employed (at most 5% of the water consumption is covered by drawing natural drinking water).

Measures for performance optimization or consumption minimization are not evaluated as autonomous units (e.g., examination of the equipment's water efficiency or assessment of the implementation of such measures); of course, a better performance due to solutions of this kind is assessed via the consideration of the total water consumption. It is indicated in [10] that a series of relevant criteria in [9] list strategies that can be applied as potential improvement solutions. These strategies include water efficient - performing over specific baselines– equipment (fittings & fixtures), the reduction of water used for irrigation, issues related to water use metering, etc.

Finally, it is noted that the reference to rainwater within the *environmental category* "Sustainable Sites" addresses its management (e.g., practices of low impact aiming at the partial reuse of the rainwater falling on the site, related systems' maintenance).

Table 3. Examination of water use, efficiency and management in LEED Operations and Maintenance v.4.1 ("Water Efficiency" *environmental category*)

Thematic area	Inclusion in the method's structure	Main aspects assessed and examined
Monitoring	The relative considerations are listed among the required-to-be fulfilled conditions of the sole *criterion* included in the *environmental category*; they constitute an assessment prerequisite.	Requirement: water meters that measure total potable water use coming from all resources (incl. Reclaimed water) are permanently installed. Requirement: measurement on monthly basis for one year.
Total water consumption	Examined within the sole *criterion* of the *environmental category* (requirement and basis for the obtainment of more points).	Evaluation of the "water performance score" against tabulated values. A minimum value is a requirement for the assessment to proceed.
Measures for consumption/use minimization/ optimization	Referred to as a means for performance improvement.	It is stated that strategies listed in related criteria in [9] can be employed for the building's performance enhancement.
Reuse of reclaimed water (greywater, rainwater etc.)	Handling this issue within the monitoring strategy of water use, and the calculation of water performance score.	Within the monitoring strategy: the total water use required to be measured includes also reclaimed water (rainwater, greywater & other sources). Within the calculation of water performance score: distinction between potable water use and reclaimed water use is made during the data input.

4 Conclusions

The preceding analysis highlighted strong similarities and differences among the three examined methods with regard to their basic features and the assessment philosophy that they employ, as well as to the way water-related parameters (efficiency, consumption, management) are assessed and implemented in their context (metrics/indicators/criteria used, relevant weights of the relevant sections, etc.).

Indicatively, the strong performance-based component is listed among the main similarities. Indeed, the monitoring of the actual water use/consumption is a central consideration in all three schemes, with features of this process (type and abilities of metering devices/ monitoring means, etc.) being explicitly specified. These characteristics, as well as other issues (e.g., whether the related requirements are mandatory or not for the assessment to proceed) vary to different degrees among the examined methods. Another similarity lies in the fact that the calculation and assessment of the actual total water consumption is shared as a concept. However, the way of points' obtainment (assessment basis) is not of a uniform philosophy. For example, the relativity element (i.e. consideration of buildings similar/comparable and or technically innovative) is explicitly inherent in the assessment process, partly or structurally, of some of the examined methods. In all cases, the use of recycled/reclaimed water (rainwater, graywater, blackwater, etc.) is strongly acknowledged and rewarded, again via varying routes. The same applies for the water use reduction measures, which are addressed in several ways: assessed as autonomous items (equipment's efficiency evaluation), integrated in a holistic approach to performance improvement, or referred to as possible improvement strategies, they are an essential part of the analysis. Another important similarity of general nature among the three methods is the strong consideration of management processes, which are either a structural part of the analysed criteria assessment, or additional requirements described in other sections of the scheme.

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Circular Business Models and Economic Viability of Circularity Solutions

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Models of Circular Economy Principles

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Abstract. Various models of Circular Economy (CE) principles have been developed in various sectors. This paper tries to give an overview of the main existing models found in literature. It explains the origins and evaluates the purpose by classifying the underlying definitions. It then compares the different models, explains the limitations and concludes with resulting principles for real estate applications. It takes a closer look at existing circular economy principles and which circular economy principles can be applied for space and infrastructure. The research approach is based on an extensive literature review of existing CE models and underlying principles in the built environment. A stepwise analysis is applied to each model. A collection of CE models is presented that helps to complete our understanding of the opportunities and limitations of CE strategies. This study analyses the existing CE models in a comprehensive manner. By comparing the different origins is manages to explain the opportunities and limitations of the different models. Providing the knowledge results in a better understanding of current CE strategies is a valuable addition to our current understanding of CE business models in real estate management.

Keywords: circular economy · lifecycle · CE principles

1 Introduction

1.1 Circular Economy in Facility Management

Various environmental problems such as biodiversity loss, water, air and soil pollution, resource depletion and excessive land use are increasingly threatening the Earth's life support systems. Especially in today's linear economic models with the "take, make, dispose of" concept raw materials are extracted, processed, used and then disposed of as waste [1]. This approach leads to a high consumption of limited natural resources [2, 3].

Traditionally, the construction industry has also historically pursued an unsustainable, linear economic model based on the "take, make, dispose of" concept and seems to continue to do so (compare e.g. EMF, 2015) [4]. This linear approach does not allow for the targeted dismantling of buildings and the reuse of materials, components, or elements in order to conserve or conserve resources and reduce the need for new raw materials [5]. The built environment plays a significant role in terms of resource consumption due to its

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significant environmental impact, but at the same time it also offers great opportunities to reduce energy consumption, greenhouse gas emissions and waste emissions [6].

A look at the annual status reports of the United Nations Organizations (UN), the International Energy Agency (IEA) and the Global Alliance for Buildings and Construction (GABC) shows the importance of the construction and real estate industry in the global context of energy consumption – the industries in question are responsible for 36% of global energy consumption and 39% of CO2 emissions [7]. The figures from 2015 underline the importance of construction in energy and material consumption, also in Switzerland, where, for example, 40% of energy and 50% of material inputs were consumed, while at the same time 75% of waste was generated by this sector [8].

It is becoming clear that there is an urgent need for a transformation of the construction and real estate industry towards a circular approach. This is where the circular economy strives for better management of resources.

Guerra et al. (2021) research and a growing number of policy initiatives are increasingly focusing on implementing a circular economy in the real estate and construction sectors [9]. This trend is also a response to the increasing pressure due to dwindling natural resources, rising waste production and increasing building material costs. Çetin et al. (2021) argue that the industry is also generally considered to be highly fragmented and characterized by high material usage [10]. These authors advocate for the restructuring of existing structures and processes, along with the development of new holistic models to include the entire value chain from raw material extraction to production, construction, use and disposal [10]. Such approaches enable the closure of material cycles and facilitate more targeted control of resource consumption and waste. According to Wilts (2021) it is crucial to not only focus on optimizing energy consumption but also to address other methods for reducing CO2 emissions [11].

Despite various approaches in the literature on the implementation of the circular economy in the sector addressed, there seems to be a lack of a structured overview or a comprehensive model of possible strategies and a uniform understanding of the term (see also e.g. Adams et al., 2017) [12]. So far, the focus has mainly been on individual aspects of the circular economy, such as the planning, recovery, and reuse of building materials for new buildings. In the meantime, the circularity for existing buildings is also increasingly being investigated in various studies [13, 14]. However, an in-depth examination of the circular economy and its application is necessary, especially in practice and especially in the field of REFM, in order not only to reduce the ecological footprint of the industry, but also to focus on an optimized use of existing buildings or even completely new service-oriented circular economy models (compare also with e.g. Kyrö, 2020; Ness & Xing, 2017) [14, 15].

Ultimately, it can therefore be stated that existing models show rudimentary cycles and aspects of the circular economy – their location in the respective model is either incomplete or one-dimensional, for example by only showing activities at the end of the service life (compare also Antunes et al., 2021) [16], a specific resource flow or material component (compare with R. J. Geldermans, 2016) [17], or a single life cycle phase (compare with Eberhardt et al., 2022) [18] why there is a need for action for the development of a holistic circular economy overview mode [10, 19].

2 Purpose of This Study

This work aims to provide a structured and comprehensive overview of circular economy principles for buildings, acting as an overview model. It particularly considers a variety of circular economy models for resource areas such as waste, CO2, energy, materials, soil and water. However, this overview model is not confined to the individual resource areas alone; it focuses on buildings to capture the essential aspects of possible circular economy principles throughout their entire service life, though it does not claim completeness in terms of models and principles.

For this purpose, an overview of different circular economy models is presented. Ultimately, this overview serves as the basis for developing circular strategies for real estate and facility management (REFM) business processes for space and infrastructure.

The following research questions, are ultimately to be answered:

– Research question 1: Which generic circular economy strategies exist for the building life cycle and in which life cycle phase can they be located?
– Research question 2: Which circular strategies can be identified in terms of space and infrastructure?

3 Methodology

Step 1: Determine search terms. The following search terms, as well as variations and combinations thereof, were defined in German and English and used as an introduction to the research.

– Circular Economy (Switzerland/EU)/Circular Economy (Switzerland/EU)
– CEN/TC 350/SC 1 and ISO/WD 59004
– Circular Economy in the construction industry (example/examples)
– Green deal
– Recycling construction industry/Recycling construction industry
– Environmental Performance of Buildings (EPB)

Step 2: Carry out a literature search: The terms were researched on the Internet and in relevant online libraries.
Step 3: Evaluate search results and select literature: Based on the assignment, suitable sources and literature were searched for the individual topics, the sources were checked for content and accuracy and the best sources were used for the work.
Step 4: Identification which generic circular economy strategies exist for the building life cycle and localization of their life cycle phase.
Step 5: Identification of circular strategies in terms of space and infrastructure.

4 CE Definitions and Principles

Desing et al. (2020) highlight the lack of consensus and a uniform definition for "circular economy", despite its widespread use (also see Kirchherr et al., 2017) [20, 21]. According to them, the Ellen Mac Arthur Foundation (EMF) definition, which emphasizes the regenerative economy and new business models, is the most cited and recognized. This definition has been widely adopted or modified by policymakers and institutions like the European Commission [4, 20, 22].

The Laboratory for Applied Circular Economy (LACE) proposes a resource-based definition of the circular economy, aimed at human well-being, but acknowledging bio-physical and planetary boundaries [23, 24]. These limits are considered absolute and quantifiable for the resource base used for human activities [24]. Definition of the circular economy is:

The circular economy is a model that adopts a resource-based and systemic view and aims to take into account all the variables of the Earth system in order to maintain its viability for people.

The model serves society to achieve well-being within physical and planetary boundaries. This is achieved through technological innovations and new business models that provide the goods and services needed by society and lead to long-term economic welfare. These goods and services are produced with renewable energy and are made from materials that are either renewable through biological processes or can be safely kept in the technosphere, requiring minimal raw material extraction and ensuring safe disposal of the inevitable waste and distribution in the environment.

Circular economy builds on, manages, and optimizes the use of sustainably available resources by minimizing entropy production, slow cycles, and resource and energy efficiency [27, p. 6].

5 LACE Model

According to LACE (2020) a sustainable circular economy means that all economic and social decisions are based on the planetary boundary can be derived [24, 25]. It consists of a three-level hierarchy of environment, society, and economy, which are connected to each other in a cascading fashion. The environmental level forms guardrails for human activities or for society, which is part of this biosphere. Desing et al. (2020) argue in this regard that human activities should take into account the natural, non-negotiable, physical and environmental constraints of the environmental level in order to be sustainable in the long term [20]. Furthermore, according to Desing et al. (2020) also for third-level economic operators, who have to operate within these environmental constraints and therefore have to comply with these restrictions in accordance with LACE (2020, p. 3) as «… Absolute and quantifiable limits to the resource base” [20, p. 3]. To ensure an efficient use of available resources, the LACE (2020) focus on the three principles [20].

5.1 RESOLVE Model

The EMF’s RESOLVE Framework describes further circular principles [26]. According to Kyrö (2020), the EMF’s framework is probably one of the most widely used models in the field of circular economy [14]. EMF (2015) further points out that the principles can be used by both companies and governments to bring about a transition to a circular economy or to develop circular strategies [4].

5.2 "Butterfly" Model

Developed by the EMF (2015), the CE model – also known as the "butterfly diagram" – is basically based on three principles [4]. In the model of the EMF (2015) a distinction is also made between a biological and a technical cycle. The biological cycle refers mainly to products or materials that are biodegradable and can be safely returned to the biosphere. In the biological cycle, concepts are also described that return nutrients to the soil and contribute to the regeneration of nature (*The biological cycle of the butterfly diagram*, n.d.). The technical cycle provides different phases that help to keep products or materials in use and not become waste. In the phases, a distinction is made between inner and outer phases or loops. Internal phases such as sharing, maintenance or reuse should take precedence over external phases (e.g. recycling), as these preserve the value of a product or preserve the product as a whole and not dismantle it to make it again, as is the case with recycling. The outermost phase, recycling, thus represents the final stage of a circular economy. Products or materials should therefore be designed in such a way that they are designed for the individual phases (e.g. easily repairable products or a modular design with the possibility of replacing individual components, etc.) and thus the full potential of a circular economy can be exploited (*The technical cycle of the butterfly diagram*, n.d.).

5.3 FOEN Model

Like the butterfly model of the EMF, the circular economy model of the Federal Office for the Environment (FOEN) also shows a biological and a technical cycle, but these are not explicitly addressed in the model itself. In contrast to the butterfly model, on the other hand, the individual phases of products and materials are shown in the technical cycle, starting with the extraction of raw materials, followed by design & production, distribution, consumption & use and the final phase recycling & collection or incineration & landfill (FOEN, 2022) [26].

Comparable to the butterfly model, on the other hand, are individual cycles or loops within the technical cycle such as sharing, reusing, repairing and remanufacturing/overhaul. In this regard, the FOEN refers to these loops within the technical cycle mentioned above – i.e. sharing, reusing, repairing, and remanufacturing/overhauling – and should not only increase the service life and service life and lead to protection of the environment, but should also be preferred over recycling, the last resort of a circular economy, so to speak. This is justified in particular by the fact that recycling in turn requires energy, water and chemicals to recycle materials and thus has an environmentally harmful effect (FOEN, 2022) [26].

5.4 UNEP Model

Another notable circular economy model includes the United Nations Environment Programme (UNEP) [27]. As in the previous two models, the UNEP model is based on a linear economy but without distinction between a biological and technical cycle [27]. Apart from this, however, so-called "value preservation loops" are shown in the model and are referred to as "user to user" (purple), "user to business" (green) and "business to business" (blue) and are briefly explained in (*Understanding Circularity*, n.d.) [27].

5.5 European Commission Model

The European Commission's Circular Economy model focuses on principles such as waste reduction, resource efficiency, and recycling. It advocates for eco-friendly construction materials, energy-efficient building designs, and the incorporation of reuse strategies throughout the building lifecycle [22]. This model, shifting away from the traditional 'take-make-dispose' approach, offers a practical framework also for the real estate development that minimizes environmental impact while potentially reducing costs and fostering new business opportunities.

6 Results

In the following, relevant circular economy models are compared, although there is no claim to exhaustiveness with regard to the coverage of all relevant models. Both definitions, principles and the models presented serve as an introduction to the topic of circular economy to familiarize the reader with various terms and aspects (Table 1).

Table 1. Summary of CE principles.

LACE	RESOLVE	Butterfly	FOEN	UNEP	European Commission
Reduction of entropy generation in the use of resources	Regenerate Share Optimize Loop	Preserve and strengthen natural capital	Sharing Reuse Repair Reprocess	Reduce by design Refuse	Durability - Minimization of total cost of ownership - Promote longevity over the life of service - Maintenance of buildings and their components
Strive for durability and longevity for the preservation of material values	Virtualize Exchange	Optimizing resource yield through products, components and materials	Recycle Prepare	Value Retention Loop: Repair Refurbish Remanufacture	Adaptability - Extending the life of the building as a whole, - possible future changes of use with a focus on substitution or refurbishment - Prevention of early demolitions
Optimize the use of resources to preserve available resources		Promote the effectiveness of the system		value preservation loop: Repurpose Recycle	Reduce waste and facilitate high-quality waste management

Based on the analysis above, applying this model to real estate lifecycle management involves integrating the following principles (Table 2).

In addition, the "Material Circularity Indicator" developed by the Ellen MacArthur Foundation [4] was further elaborated to the Madaster CI. It is displayed for the entire building on a scale of 0 to 100% and refers to the data recorded in the "material passport" or in the Madaster database [28, 29].

Table 2. Summary of CE principles.

Principle	Description
Resource Efficiency	Reducing Entropy and Optimizing operation
Regeneration	Improving the state of human and eco-logical systems through the use of renewable and healthy resources
Reduce	Restricting resource flows throughout the life cycle of buildings (Share, Reuse, Repair)
Decelerate/slow	Slowing down resource flows by intensifying use and extending useful life
Closing	Returning resources to the cycle at the end of their life
Cooperation	Fostering collaboration between supply chain actors
Digitalization	Efficient handling and systematic collection of information and data over the entire life cycle of a building to increase transparency, traceability and optimization of processes

The UNEP model maps circular processes or strategies (see, for example, reuse, refurbish or recycle), but is also assigned to the already mentioned value retention loops "user to user", "user to business" and "business to business". The overarching principle is "Reduce by design", which exerts the greatest influence and the "business to business" value retention loop has the least influence on the circular economy [27].

The application of CE principles in real estate, building design and use (adaptability, durability, waste reduction and high-quality management according to the European Commission (EC 2020)) is mainly focused on new buildings where circularity can be embedded and facilitated since the early design stage and consequently throughout the whole life cycle of a building and its components and materials. Conversely, circularity in the context of existing buildings is not so far defined (compare Kyrö 2020) [14].

On the other hand, less has been said about the design aspect of circularity integration in buildings (e.g. design for disassembly (DfD), design for adaptability (DfA), design for change (DfC) etc.) and the role of building professionals and supply chain elements in embodying the CE principles into the building sector as also Kanters (2020) pointed out [30]. In other words, existing practices and concerns focus on the CE principle of "closing the loop" which assumes intensified reuse and upcycling of materials and components.

Meanwhile, the CE principle of "slowing the loop" that suggests increasing building and product longevity by preserving their value, quality, and efficiency to the highest possible extent has received less attention so far. This can be justified by the influence of the prevailing construction and design culture during the last decades of viewing buildings as temporal products of limited life service and predefined destiny – demolition. Another key principle of CE that is rarely addressed by existing frameworks is "narrowing the loop" which relies on using fewer resources per product. This principle is inspired from nature's processes that mainly use a limited chemical palette often consisting of six elements: carbon, hydrogen, oxygen, nitrogen, phosphorus and sulphur, while industrial manufacturers follow a different approach, seeking out rare and toxic elements to reach the desired functional properties. Narrowing the loop delivers conditions for recycling by allowing efficient and facilitated material separation and recovery.

7 Conclusions

A collection of CE models is presented that helps to complete our understanding of the opportunities and limitations of CEM. This study analyses the existing CE models in a comprehensive manner. All important key strategies for the application of the circular economy over the entire life cycle of a building circular economy strategies in general were collected. Its applicability for the built environment was reviewed.

Research question 1 could be answered: The multitude of definitions of CE, and more specifically circularity in the built environment, does not contribute to a coherent, systematic approach. CE needs to be viewed as a business strategy, not only waste management or a design strategy. Optimising buildings' use should also be spotlighted instead of only viewing those as potential material banks where components and materials can be recovered, reused or recycled for new constructions [12, 17]. Still, recovered materials from existing buildings face a critical barrier in their technical compatibility and quality appraisal, which put their direct reuse in question, leading to downcycling processes and engaging extra resources and energy flows.

Research question 2 could be answered: The circular economy is seen as a regenerative system in which resource use and waste as well as emissions and energy losses are minimized, waste is avoided and material and energy cycles are slowed down, closed and narrowed. This can generally be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing or recycling. In the context of the real estate and construction sector mentioned, this means that no new resources are required in the production of materials and waste is also minimized. In addition, better resource management is sought by reducing consumption (or even avoiding unnecessary consumption) and striving for resource circulation through the reuse or recovery of materials, components or components.

The strategies could be assigned to the individual life cycle stages of a building, and differentiated between the design, construction and end-of-life phases. Some key strategies are explicitly focusing on specific life cycle stages, such as Material Banks, Design for adaptability, etc. On the other hand, most strategies include some sort of information and data management, like Adoption of Efficient Processes, Waste as a Resource, and Resources Data Management. By comparing the different origins it explains the opportunities and limitations of the different models. Providing the knowledge gaps is a valuable addition to of our current understanding of CE.

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Multi-scalar Business Models for Advancing Circular Economy in Real Estate Development

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Abstract. Cities face the challenge of addressing urban vacancies due to market volatility, rapid shifts in needs, demand, user preferences, or issues related to financing, planning, or delays in building approvals common in cities like Zürich. The study delves into a transformative shift in the Swiss real estate market, emphasizing the integration of circular economy principles, impact investments, and digitalization. The research approach is mainly descriptive, drawing upon case studies of temporary use urban projects. It incorporates a review coupled with the application of design thinking in the development of a digitalization model. In Zürich, the temporary use of vacant buildings is predominantly as office space showing a limited multi-scalar impact. In contrast, in vacant sites, Nature-based Solutions interventions demonstrated high multi-scalar impacts, enhancing biodiversity, air quality, and resident well-being, and aligning with circular economy principles. Meanwhile, various flexible uses of vacant sites indicated moderate impact, promoting innovation and new business models. A digitalization model is proposed to re-purpose these sites in circular rather than linear economy. The research underscores the importance of temporary, flexible uses on vacant site as platforms for testing new multi-scalar impact investment ideas and establishing the financial profitability of nature-based solutions in urban contexts. The study highlights the potential of temporary urban land use to promote swift urban transformations, balancing financial returns with ecological impacts for advancing circular economy.

Keywords: Nature-based Solutions · Digitalisation · Temporary Use · Impact Investments · Urban Transformation

1 Introduction

The focus of this research lies on urban epicenters, such as Zürich, which are marked by a high demand of both residential and commercial real estate. In these urban landscapes, several challenges - regulatory, logistical, and fiscal - often hinders the advancement of investments in construction initiatives. This phenomenon leads to a widespread issue where numerous sites remain vacant for extended periods. By addressing the principles of the circular economy, this study aims to confront these challenges, investigating methodologies and new business models to repurpose these temporary vacant spaces into functional areas. This entails a reevaluation of site development strategies through

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inter-scalar tactics to advance circular economy, tapping into digitalization to show the benefits of temporary use with flexible structures and Nature-based solutions (NBS).

2 Literature Review

2.1 Flexible Structures and NBS for Temporary Use of Vacant Sites

The concept of implementing temporary, incremental, and flexible strategies for urban vacant land use is a practical response to the diverse conditions and contexts of vacancy, as explored by research. This model emphasizes flexibility and adaptability in urban planning and design, which is particularly relevant in the context of circular economy to manage vacancy [1].

Predominantly, the discourse around urban vacancy has been centered on shrinking cities, where socio-economic decline result in abandoned or underutilized spaces [2]. However, the scope of this research extends beyond these contexts to include growing cities, such as Zurich, where demand for urban space is high, yet the need for strategic vacancy management remains critical. This paper seeks to bridge the gap in existing literature by exploring how urban strategies can address vacancy in high demand urban areas by responding to challenges such as market uncertainty, rapid change in the needs, demands and user preferences.

Moreover, the model is more appropriate for public ownership, where uncertain transitional periods can be exploited [1], there is a gap in temporary use models suitable for institutional or private investors, who are interested in high financial returns. Therefore, this study considers the value dimensions, in particular the value creation mechanisms of temporary use for sites waiting for building permit approvals, planning, or financing.

Existing studies reveal a range of temporary urban solutions which have been explored and implemented. These temporary pop-up environments are characterized by modular structures which allows for temporary occupation and adaptability to different uses, needs and target groups, though international transferability is limited due to the importance of local context [3]. The case studies include temporary housing from shipping containers, event space, pop-up retail [4].

In this context, integrating NBS into urban development is a crucial strategy. As defined by the European Commission in 2015, NBS approaches use nature to address global challenges, providing economic, social, and environmental benefits. They are part of green infrastructure, targeting specific issues. The concept has developed further, as Langergraber et al., 2020 [5], under the European Cooperation in Science and Technology's Circular City initiative, highlight. Here, NBS involves incorporating nature into cities and using natural processes to address challenges like the heat island effect through microclimate improvement, air pollution through carbon sequestration, social inequity, biodiversity loss in urban ecosystems [6, 7, 19]. Additionally, empirical evidence, as exemplified by Dwaikat et al., 2016 [8], indicates NBS‘s potential to increase real estate values.

2.2 Multi-scalar Impact Investments for Temporary Vacant Sites

The business case for circular economy models for flexible, temporary use including NBS for real estate investors remains challenging. Most of existing flexible re-use solutions are on temporary vacant sites waiting densification approvals rather than being permanent solutions. We identify here an opportunity to prove the feasibility of a more adaptable, incremental, and flexible urban development. To address this challenge, the review is addressing the recent paradigm shift in the real estate industry from the responsible to impact investments. It is driven by emerging regulations such as the EU Taxonomy [9], aiming to channel capital investments into decarbonization, circular economy or biodiversity measures. The challenge lies in balancing these sustainable measures with financial yields. Impact investments, aiming for social or environmental impact in addition to financial return, is not a new concept, it was only coined in 2007 by the Rockefeller Foundation [10]. This approach aligns with the concept of social entrepreneurship, which integrates profit-making with philanthropic goals, a principle increasingly applicable to real estate development. Entrepreneurial management, essential in real estate development, is highlighted in this context [11, 12] (Fig. 1).

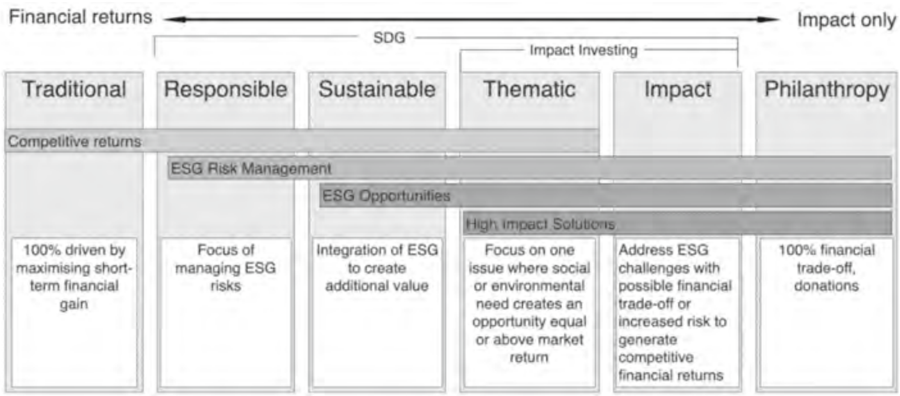

Fig. 1. Classification of sustainable investments, based on the European SRI Study 2012, INREV.

The financial sector is exploring the potential of innovative impact investment products by increasing risk and entrepreneurship [13]. The challenge is to find the balance between directing capital towards these measures without compromising yields. One strategy is tapping into the multi-scalar value generation of urban transformation solutions integrating NBS. The temporary use sites act as a platform for new impact invest products to be tested and developed.

2.3 Capturing the Multi-scalar Value with Digitalization

Numerous studies have highlighted the necessity and challenges of evaluating the diverse impacts of urban interventions across various scales. Hayek et al. (2015) [14] explore the intricate relationship between real estate supply and open space, assessing urban interventions from individual parcels to city regions. Despite these efforts, accurately valuing these impacts at multiple scales remains difficult. Recognizing the importance of considering both local context and broader implications, this study seeks to transform these challenges into a business opportunity. It aims to investigate the potential of digitalization to assess and capture the multi-scalar value of urban interventions on temporary vacant sites.

With the advancements of open standard data models, which solve the interoperability issues, Noardo et al. (2020) [15] discuss the integration of 3D city models and GIS datasets with Building Information Models (BIM) through GeoBIM, enabling inter-scalar urban analysis. The use of AI algorithms can further enhance our interpretation of the urban environments [16]. The successful translation of the multi-scalar urban analysis synthesis into design criteria can benefit from the advancements in parametric and algorithmic design [20]. Particularly concerning the circular economy and the variety of temporary re-use scenarios of vacant sites, the application of parametric and algorithmic design can be used to control and optimize various aspects of a project in early stages, allowing for the exploration of multiple design scenarios and alternatives [17]. The decision-making process can be supported by using these technology enabled insights to manage the trade-off between the financial impact and the environmental gains, for example balancing urban densification scenarios with NBS.

The already established BIM and Digital Twins technologies have significant potential for enhancing the construction and maintenance of flexible structures and NBS on temporary vacant sites. BIM provides a detailed 3D model and a Common Data Environment (CDE) with digital information useful for project management, monitoring, and operation across the entire lifecycle of a project. When combined with Digital Twins, this approach contributes to a circular economy by facilitating optimized asset management, enabling stakeholders to visualize, share data, and monitor conditions in real-time, leading to efficient cost management, reduced project delivery time and disassembly [18] in particular relevant for temporary re-use.

3 Methods and Research Approach

A comprehensive mixed-method approach was utilized, combining literature review, case studies, and design thinking methodologies as outlined in Table 1.

Table 1. Research Design.

Method	Description
Literature Review	Themes: digitalization, impact investments, multi-scalar impact of NBS, temporary use
Case Studies	1. Vacant Real Estate: - Screening of 38 temporary use offers in Zürich region via Projekt-Interim data set 2. Vacant urban plots: - Identifying temporary uses: - Fogo Vulkanplatz – mixed use from shipping containers - Josef-Areal – Recycling and Circular Economy Center 2024–2032 - Frau Gerold Garden - Pop-Up urban gardening, gastro, market 3. NBS Case Studies: - Project Uetikon am See, Zürich
Design Thinking, Action Research	Based on the identified problem and business opportunity, developing a model to leverage digitalization to implement circular economy business models on temporary vacant sites

4 Results and Discussion

4.1 Multi-scalar Value Generation of Temporary Uses in Vacant Real Estate

Limited Scope and Multi-scalar Impact. The findings indicate a constrained scope and impact across multiple scales. From a total of 38 cases, the majority is temporary office space. In addition, storage space and very few residential, retail and parking is being offered for temporary use. In terms of rent per square meter, the revenue generated is relatively low, barely covering the operational costs of assets that are non-sustainable and awaiting upgrades, repurposing, or demolition (Table 2).

Table 2. Multi-scalar value generation of temporary use in vacant real estate.

Time Span	Multi-scalar value generation			The Value for the Investor
	Local Value	Neighborhood Value	City Value	
Temporary Use: mainly – offices; Other – storage, residential, parking				
3 to 24 months	Immediate local supply of temporary office space, co-working space	Limited Impact	Very Limited Impact	Generates very low rental income barely supporting operation costs of non-sustainable assets waiting for upgrades, re-purpose, or demolition

Moderate Scope and Multi-scalar Impact. The flexible uses of vacant sites offer opportunities for innovation, new business models, new site uses which generate a moderate multi-scalar impact as analyzed in Table 3.

Table 3. Multi-scalar generation of temporary use in vacant sites after demolition.

Time Span	Multi-scalar value generation			The Value for the Investor
	Local Value	Neighborhood Value	City Value	
Pop-Up Retail or Food Outlets: Temporary structures for small businesses or food vendors				
Several months	Immediate employment and services	Vibrant amenities	Low economic impact through increasing diversity	Generates rental income; increases site visibility
Temporary Event Spaces: Spaces designed for short-term events, exhibitions, or markets				
Several months	Local cultural and social activities	Visitor attraction; more vibrant district	Moderate Impact	Short-term revenue; marketing opportunities for future developments
Art Installations: Temporary art projects or installations that engage communities and add cultural value				

(*continued*)

Table 3. (*continued*)

Time Span	Multi-scalar value generation			The Value for the Investor
	Local Value	Neighborhood Value	City Value	
6–12 months	Cultural value and aesthetic appeal	Neighborhood identity	Moderate Impact on the cultural landscape	Attracts public interest; enhances the site's aesthetic value
Recycling Center: A center to bring, sell, or repurpose promoting circular economy				
1–3 years	Recycling and entrepreneurship	Neighborhood sustainability	Waste reduction and recycling support	Contributes to social responsibility; potential for government incentives
Temporary Living: Modified shipping containers providing temporary accommodation for specific users				
1–5 years	Affordable housing for specific groups	Housing shortages temporary solution	Limited impact on housing demand/supply	Steady rental income; social impact investing
Logistic and Storage Facilities				
1–5 years	Storage for local businesses	Shorter delivery times	Limited impact	Moderate rental income; low maintenance requirements

High Scope and Multi-scalar Impact. NBS interventions deliver significant multi-scalar impacts. Even small green interventions at the plot-scale contribute to a broader ecological network, addressing various socio-ecological challenges as confirmed by literature [21]. These include biodiversity preservation and ecosystem services, improved air quality, and enhanced health and well-being for residents. By integrating the diverse values of NBS into urban strategies through vacant land use, urban resilience is strengthened by promoting adaptability and flexibility (Table 4).

Table 4. Multi-scalar impact of NBS on vacant sites.

Time Span	Multi-scalar value generation			The Value for the Investor
	Local Value	Neighborhood Value	City Value	
Green Spaces and Public Parks: Temporary parks or community gardens				
1–3 years	Environmental quality and recreation enhancement	Community and social impact	Green infrastructure addressing biodiversity loss, stormwater management, carbon sequestration	Increases property added value;
Urban Farming				
1–2 years	Sustainability practices engagement	Food security and community bonding	Urban agriculture support	Enhances site value through sustainability initiatives
Sports and Recreation Facilities: Temporary sports fields, courts, or small parks for community recreation				
6–18 months	Health and well-being	Social cohesion	Contributing with public health amenities	Increases community acceptance; potential for sponsorship opportunities

The main findings are summarized in Fig. 2.

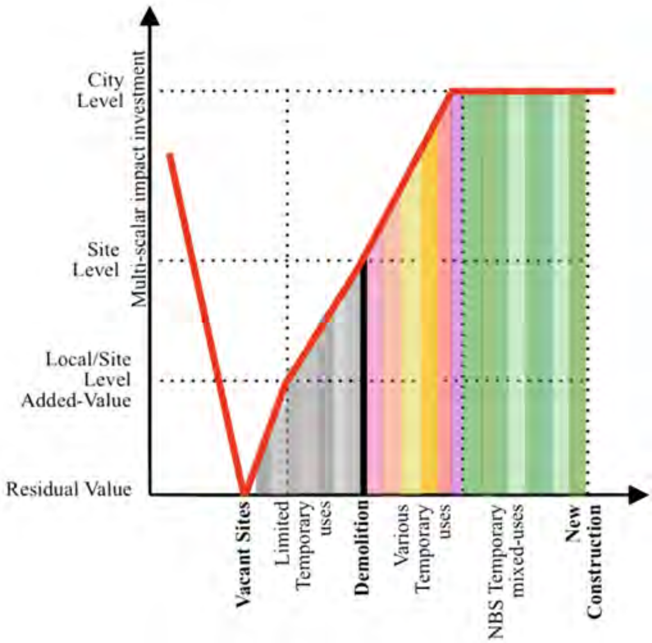

Fig. 2. Multi-Scalar Impact Investments.

4.2 Scenario Planning with Digitalization

Multi-scalar Site Analysis. Utilizes GeoBIM and AI algorithms to understand the site constraints and possibilities ranging from local to the regional scale.

Multiple Scenario Generation. Utilizes parametric and algorithmic design to create multiple temporary use scenarios, factoring in owner requirements, market trends, demand, site limitations, and regulations.

Multi-scalar Impact Assessment. Evaluates scenarios based on cost-benefit analysis and overall value generation, identifying the solution with high financial return and high environmental impact.

Matchmaking. The platform connects suppliers of temporary, modular structures and owners of vacant sites, promoting efficient resource utilization and temporary site use.

Detailed Planning and Execution. Facilitates collaborative planning for the chosen scenario via CDE enabled by BIM.

Maintenance. Digital Twins for managing the temporary use for the owner over the short life cycle.

Disassembly. After the temporary uses, facilitates the disassembly and listing of structures on the platform at different sites.

5 Conclusion

The study is centered on applying the principles of the circular economy to address the underutilization of vacant urban land while promoting a swift urban transformation. It explores the temporary use of vacant land in cities like Zürich as a testing ground for new real estate products and ideas, facilitated by emerging digital technologies. This approach minimizes physical planning and waste, providing innovative solutions to rapidly evolving user needs and demands. By using digital tools to analyze trade-offs between financial returns and the ecological impacts of various urban scenarios, the study advocates for NBS and more flexible urban development. This digital methodology aligns with the circular economy's goals of maximizing resource efficiency and minimizing waste. Thus, the study suggests that the flexible and temporary use of land, particularly during periods of transition or uncertainty, is a valuable strategy for urban development. This approach is applicable not only to publicly owned lands but also to those awaiting development by private and institutional investors.

The paper introduces a new multi-scalar approach to manage urban vacant land. It proposes the use of temporary, flexible structures in conjunction with NBS as a strategic method to manage such spaces and their impact on local, district and city scale. This method is particularly beneficial in high-demand cities where it presents a sustainable solution for preserving open spaces while adapting to the changing needs, demands, and preferences. In conclusion, the strategic management of vacant spaces, as proposed in the study, is crucial not only for the functionality of urban areas but also for preserving valuable open spaces. This approach demonstrates the potential for temporary and flexible land use strategies within the framework of a circular economy, offering a model for sustainable urban development.

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Assessing the Impacts of Urban Circular Economy Practices on Economic Growth, Environmental Sustainability, and Social Benefits: A Case Study Analysis

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Abstract. The urban circular economy is a highly effective approach to both waste management and the utilization of resources. Many cities have already adopted best practices based on circular economy principles. However, implementing such practices requires multi-stakeholder engagement, new business models, and collaboration between cities. Some successful strategies exist, ranging from urban agriculture and waste-to-energy to sharing economies, industrial symbiosis, and sustainable mobility, as well as eco-design, waste prevention, and the extension of product life. By adopting circular economy practices, cities can support economic growth, reduce environmental impact, and create social benefits, thereby moving towards a more sustainable future. In this regard, this study aims to analyze circular economy practices at the urban circularity level, by assessing their impacts on economic growth, environmental sustainability, and social benefits. To achieve this goal, a literature review is conducted to identify the most widely adopted circular strategies in cities. Comprehensive data collection, encompassing quantitative and qualitative measures, including economic indicators, environmental metrics, social assessments, and stakeholder feedback on the implementation process. Then the case study of Amsterdam is selected to demonstrate how urban circularity can be effective in achieving a balance between economic growth, environmental sustainability, and social benefits. Finally, this study also provides insights into the potential of urban circularity as an effective tool for sustainable urban development.

Keywords: Urban Circular Economy · Sustainable Urban Development · Economic Growth · Environmental Sustainability · Social Benefits

1 Introduction

Cities are dynamic and complex entities shaped by a diverse array of actors, organizations, and networks. Considering cities as crucial players in the global shift towards sustainability, city managers, including policymakers, urban planners, and mayors, have the potential to take the lead in addressing urban sustainability challenges and combating climate change [1, 2]. In this regard, local governments possess comprehensive

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knowledge of their surroundings and have the authority to govern and make decisions regarding urban planning, water management, waste disposal, and public transportation [1].

Urged by the impending exhaustion of natural resources and the growing burden on landfills, innovative eco-cities are proactively adopting waste reduction or zero-waste programs. [1]. As a result, the zero-waste objective was incorporated into European Union policy in 2013, and this initial plan has evolved into a comprehensive strategy for advancing the circular economy (CE) across Europe [3].

Accordingly, the urban circular economy, as opposed to the traditional linear economy of “take, make, dispose”, represents a paradigm shift towards a more resource-efficient model of “reduce, reuse, recycle, and remanufacture”. The circular economy (CE) approach is rooted in the understanding that the Earth operates as a closed, circular system with finite resources, and emphasizes the need for a harmonious coexistence between the economy and the environment [4]. This transformative approach holds immense promise for addressing the pressing sustainability challenges facing cities worldwide. Thus, cities can foster economic growth, enhance environmental protection, and promote social equity by minimizing waste generation and maximizing resource utilization.

Even though circular economy practices in cities have shown promising results, their implementation faces many challenges. Shifting an economic model from the traditional linear process to the circular one necessitates the active participation and dedication of multiple stakeholders, including producers, consumers, and policymakers [4]. Collaborative value creation among these actors plays a crucial role in ensuring the success and sustainability of this economic model, which is expected to bring about positive impacts on the social fabric of communities, the sufficiency of the economy, and the preservation of the natural environment.

This study aims to comprehensively assess the impacts of circular economy practices on economic growth, environmental sustainability, and social benefits at the urban circularity level. By examining these key areas, the study aims to provide a holistic understanding of the impacts and potential benefits associated with the implementation of circular economy practices within urban contexts. Through this analysis, valuable insights can be gained to inform decision-making and policy development towards more sustainable and resilient urban environments. A literature review will be conducted to identify the most widely adopted circular strategies in cities, followed by comprehensive data collection encompassing quantitative and qualitative measures. Finally, a case study is presented to demonstrate the implementation of a circular economy in the urban environment.

2 Literature Review

The methodological approach for this study consists of a critical review of the literature on CE implementation in the urban environment. The aim is to identify the most widely adopted CE practices in cities. The literature review was conducted using the Artificial Intelligence (AI) Tool Research Rabbit (https://researchrabbitapp.com/). Research Rabbit allows the searching in multiple academic databases, including Scopus, Web of Science, and ProQuest.

A first search was conducted by using the keywords: "urban circularity", "case studies", "circular economy in the urban environment", and "circular economy in the built environment". Then, to complement the first analysis was added the sentence "case studies in circular economy practices in the urban environment". "In this initial search, the articles were screened to identify those relevant to the research question. By skimming the titles and abstracts to assess their relevance, a total of 20 articles were selected. Figure 1 illustrates the relationship between the articles.

Fig. 1. Connections between articles. Source: https://researchrabbitapp.com/.

A second search was conducted to investigate "similar works," "earlier works," and "later works." A total of 1,537 articles were identified as "similar works," with 117 categorized as "earlier works" and an additional 293 classified as "later works." Upon thorough examination, 33 were identified for in-depth analysis.

2.1 Overall Analysis: Cities and the Circular Economy

Cities are the cornerstones of human life and their sustainable futures. Thus, in any conceptualization of a circular city, these issues must be considered. With the growing profile of the CE and its potential to engage different stakeholders, alongside the recognition of the importance of cities for addressing sustainability challenges, there is a pressing need to understand what a future circular city might look like [1].

Furthermore, urban systems hold a unique potential for circularity, shaped by their distinct social, economic, and environmental factors. CE strategies must be tailored to the specific realities of each context, ensuring their effectiveness and alignment with local priorities. Numerous reports have been published documenting successful efforts to identify and harness this potential, leading to the development of tailored circular economy implementation strategies for various urban systems [2].

The development of a CE within cities, provinces, or regions entails the integration and redesign of four key systems. These systems include the industrial system, which involves transitioning from small to large companies and phasing out heavily polluting enterprises in favor of light economic activities such as high-tech industries, tourism, or culture. Additionally, the infrastructure system delivering essential services, such as transportation, communication, water recycling, clean energy, and electrical power lines, needs to be reconfigured. The cultural framework and social system also require adaptation to support the principles of a circular economy [5].

Vanhuyse (2023) [6] put forth an urban circularity assessment framework that offers city governments and other stakeholders the ability to formulate a comprehensive CE strategy that encompasses different scales, ranging from local to global concerns. This framework is based on a hierarchical approach, starting with a strategic CE vision and sustainability targets at the highest level. These goals then guide the establishment of institutional arrangements, CE strategies, and the management of urban stocks and flows. Moreover, this framework establishes links to the triple bottom line, ensuring that economic, environmental, and social aspects are considered in the development and implementation of CE strategies.

2.2 Benefits

Pomponi and Moncaster (2017) [7] emphasized the environmental benefits of circularity, noting its potential to reduce greenhouse gas emissions and conserve natural resources. According to Geissdoerfer et al. (2017) [8], the circular economy is a powerful tool for sustainable development, emphasizing its ability to minimize waste and optimize resource flows. Additionally, the CE holds the potential to comprehend and implement transformative new patterns, enabling society to attain heightened sustainability and well-being while minimizing or eliminating material, energy, and environmental costs [5].

Several cities have embraced CE as an aspirational concept. While future-oriented, multidisciplinary, and systemic perspectives hold the potential for CE to simultaneously address economic and social issues, empirical data on circular cities is lacking [1]. Munaro et al. (2020) [9] conducted a comprehensive review of circular economy applications, identifying initiatives for circular cities and the transition to a sustainable built environment.

Hysa et al. (2020) [10] recognized the circular economy as a new governance model for sustainability transitions, requiring strategic reframing and institutional design. Çimen (2021) [11] examined the relationship between circular economy and sustainable development goals, demonstrating its potential to contribute to multiple dimensions of sustainability.

2.3 Challenges and Barriers

Despite the promising evidence, implementing circular economy practices in cities presents significant challenges. Multi-stakeholder engagement, the development of new business models, and collaboration between cities are crucial for successful implementation.

The CE implementation at the city level faces several barriers that include the need for CE adaptation of design and technology, access to material information, and additional investment for CE business models [12].

Pomponi and Moncaster (2017) [7] emphasized the importance of stakeholder engagement in shaping circular economy policies, while Munaro (2020) [3] stressed the need for new business models that align with circular principles. Furthermore, they indicate the lack of awareness and understanding of the CE among stakeholders in the construction value chain as a significant issue [9]. Hysa et al. (2020) [4] highlighted the importance of collaboration between cities to share knowledge and best practices, while Çimen (2021) [11] emphasized the role of government policies in promoting circularity.

According to Williams et al. (2022) [13] the absence of circular urban systems of provision in cities stands as the primary obstacle to the adoption of circular practices. The implementation of such systems faces two major challenges: political and economic factors. The authors also highlighted the current conceptualizations of the CE to incorporate a social dimension [13].

The CE agenda primarily focuses on businesses, fostering their competitiveness by valorizing waste for circular advantage and value creation, reflecting the growth-oriented narrative of the cradle-to-cradle framework. However, this approach may increase business control over resources and diminish citizen autonomy. Additionally, applying CE principles in businesses is a distinct undertaking from adopting CE in cities [1].

To address these barriers and facilitate the transition to a CE at the city level, Lee et al. (2016) proposed several strategies. One such strategy is the sourcing of materials locally, which reduces the need for long-distance transportation and promotes regional circularity [14]. Another important strategy is the adoption of clean transportation methods, which helps to minimize the environmental impact of logistics and contribute to a more sustainable CE. In addition, the implementation of public policies and financial incentives that promote material reuse, efficient waste collection, and the development of a robust recovery market are crucial factors in facilitating the circular economy transformation at the city level [15].

3 Discussion

Recognizing the significance of cities in addressing sustainability challenges, the urban systems possess distinct social, economic, and environmental factors that make them unique in terms of their potential for circularity. Hence, to ensure effectiveness and alignment with local priorities, circular economy strategies must be tailored to the specific realities of each context. This has led to the development of tailored circular economy implementation strategies for various urban systems.

The primary objective of this study is to conduct a comprehensive assessment of the effects of circular economy practices on economic growth, environmental sustainability, and social benefits specifically at the urban circularity level. A comprehensive analysis of the literature revealed the primary strategies and their relationship with economic growth, environmental sustainability, and social benefits, to promote circularity within urban environments. Thus, the analysis provided a better understanding of how circular economy practices can be used to stimulate economic growth, protect the environment, and create social benefits in urban environments. Also, the main challenges and barriers to implementing circular economy practices in urban environments.

The subsequent section delves into the Case Study of Amsterdam, exploring the applicability of CE practices within the city's unique context.

4 Case Study: Amsterdam

Since the 1980s, the Netherlands has been actively promoting policies related to the CE, with a particular focus on increasing recycling rates and reducing the amount of unsorted (household) waste that ends up in landfills [12].

The discussions surrounding the concept of the CE first emerged in Amsterdam in 2013. Recognizing its potential, the Amsterdam municipality included the CE concept in its sustainability agenda in 2015. In 2016, an action agenda was launched with the ambitious goal of positioning the city as a frontrunner in circularity. The Strategic Advisor for Sustainability in Amsterdam highlighted the significance of a comprehensive action program that prioritizes circularity, making the CE agenda even more impactful [1]. This agenda emphasized the importance of collaboration among various stakeholders, including local businesses, companies, and citizens [1, 12, 16].

Within this action agenda, two material streams, organics, and construction, were prioritized. For the organic stream, specific objectives were identified, including the establishment of a biorefinery hub, the promotion of cascading organic residues (such as biomass production), and the extraction of valuable resources like phosphate from waste residues. To measure progress, a clear target was set: achieving a 65% organic separation rate by the year 2020 [16].

Furthermore, Amsterdam's spatial plan primarily focused on strategic priorities such as job creation and housing for a growing population. However, it also recognized the importance of waste/bio-clusters in the port area, facilitating local circular actions. To support these initiatives, the Circular Innovation Program provided financial incentives [13]. The spatial plan also emphasized the utilization of residual heat and the preservation of green spaces within the city, both crucial for achieving circular development (CD). These efforts were further bolstered by the Sustainability Strategy and the Circular Vision and Roadmap, which outlined specific CD goals. The implementation of these goals was carried out through the Learning by Doing program [13]. Policymakers acknowledge the intricate nature of the CE and recognize its complexity [1]. Despite Amsterdam's pioneering position in this field, it is essential the need for "experimentation" due to the relatively new territory of CE and the existence of unknowns. While there are currently limited policy instruments, there is at least some framework in place. In terms of financing, an opportunistic approach is taken, focusing on providing support and incentives to existing projects that show promise and align with the city's goals. This is achieved through policy instruments such as the sustainability fund. Furthermore, policymakers emphasize the concept of creating a “future-proof” city, placing importance on resilience and adaptability rather than solely focusing on sustainability [1].

Moreover, Amsterdam is actively embracing a circular economy approach, evident in the numerous experiments underway across the city [1]. One notable example is the implementation of legislative “free zones” in the post-industrial area of Buiksloterham, where partners are encouraged to test innovative waste collection and water sanitation methods. In 2016, Amsterdam made a significant step forward by becoming a Fab City, a movement dedicated to exploring the potential of new city dynamics enabled by distributed urban production systems powered by advanced technologies such as 3D printing and smart and efficient mobility and food systems [17]. The city also houses the fully circular community of De Ceuvel, a participatory living lab of a self-sufficient community that aspires to be “at the vanguard of circular living” [18]. Residents of De Ceuvel contribute to the community’s sustainability by constructing self-build homes from recycled materials and managing their own material, energy, and food resources. This initiative aligns with the “Manifesto for a Circular Buiksloterham,” which emphasizes the core themes of circularity, bio-based solutions, and smart innovation [1, 18].

These efforts demonstrate Amsterdam’s commitment to advancing the circular economy and its proactive approach to promoting sustainable and resource-efficient practices [13].

5 Conclusion

Cities are the cornerstones of human life and their sustainable futures. As the circular economy gains traction as a sustainable development paradigm, cities emerge as crucial actors in shaping the future of this transformative concept. The CE’s potential to minimize waste, optimize resource flows, and foster a more sustainable future resonates deeply with the challenges faced by urban environments.

Furthermore, cities bear the responsibility of ensuring a sustainable future for their inhabitants and the planet. The CE presents a promising pathway towards this goal, offering a framework for resource-efficient and environmentally responsible urban development.

However, implementing CE practices in cities presents unique challenges, demanding multi-stakeholder collaboration, innovative business models, and effective partnerships between cities.

Despite the nascent stages of CE implementation at the city level, the growing interest and the increasing number of cities embracing this paradigm offer a glimpse into the future of a circular urban landscape.

The primary objective of this study was to conduct a comprehensive assessment of the effects of circular economy practices on economic growth, environmental sustainability, and social benefits specifically at the urban circularity level. A comprehensive analysis of the literature revealed the primary strategies and their relationship with economic growth, environmental sustainability, and social benefits, to promote circularity within urban environments. The case study of Amsterdam was presented to illustrate the implementation of CE practices in an urban environment. Amsterdam’s unwavering dedication to the circular economy has propelled the city into a frontrunner position. Through a comprehensive strategy that prioritizes collaboration, Amsterdam has successfully implemented numerous initiatives to foster circular practices. These efforts serve as a testament to the city's visionary approach to sustainability and resource-efficient practices. Amsterdam stands as a beacon of hope, demonstrating the transformative potential of the CE through its unwavering commitment and proactive initiatives.

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Exploring the Potential of Circular Economy Strategies in Urban Planning: A Comparative Analysis of Successful Case Studies

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Abstract. The circular economy has emerged as a powerful solution to address environmental and socio-economic challenges in urban areas. As cities continue to grow and face increasing resource demands, adopting sustainable practices becomes critical to promote resource efficiency and improve the well-being of urban communities. This study aims to assess the effectiveness and feasibility of circular economy strategies at the urban scale, focusing on urban design and resource management. By examining successful case studies from four cities, valuable insights will gained into implementing circular economy practices in urban planning, such as waste management, renewable energy, and sustainable architecture. The comparative analysis of these cases will allow an assessment of the different approaches taken by each city and their impact on the sustainability and resilience of urban environments. This study aims to inspire and guide future urban development and promote sustainability and resilience in European cities by highlighting successful examples of circular economy implementation. Ultimately, this study aims to provide a comprehensive understanding of the role of circular economy principles in urban environments, highlighting their potential to promote sustainability and resilience. Through four study cases, this study will illustrate The tangible outcomes and real-world implications of adopting circular economy practices in urban landscapes.

Keywords: Urban circular economy · urban development · sustainable practices · resource efficiency · urban planning

1 Introduction

The circular economy has emerged as a promising approach to addressing the challenges faced by growing urban areas. By adopting circular economy principles, cities can reduce their environmental impact, improve resource efficiency, and create a more sustainable future [1]. This study aims to assess the effectiveness and feasibility of circular economy strategies at the city level, with a particular focus on urban design and resource management.

The study will examine successful case studies from four cities: London, Amsterdam, Copenhagen, and Yokohama. These cities have made significant progress in adopting

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circular economy principles and can provide valuable insights into how circular practices have been implemented in different aspects of urban planning.

The comparative analysis of these case studies will allow for a comprehensive understanding of the different approaches taken by each city and their impact on the sustainability and resilience of urban environments. By examining the successes and challenges experienced by each city, the study aims to identify best practices and lessons learned that can inform future urban planning efforts.

The ultimate goal of this study is to promote the adoption of circular economy strategies in European cities, leading to a more sustainable and resilient urban landscape. By highlighting successful examples of circular economy implementation, the study aims to inspire and guide future urban development, ensuring that cities are resource-efficient, liveable, equitable, and prosperous.

Adopting circular economy principles in urban planning offers a variety of benefits. Minimising waste generation and maximising resource use throughout the life cycle of materials leads to reduced consumption and conservation of precious resources. Circular economy principles, in turn, reduce the environmental impact of cities.

Circular practices promote sustainable resource management by optimising resource allocation and establishing circular supply chains. Circular practices reduce dependence on finite resources and mitigate environmental degradation.

Urban circular economy initiatives improve environmental sustainability by minimising pollution, greenhouse gas emissions, and waste disposal. These measures contribute to a cleaner and healthier urban environment [2].

Urban circular economy practices stimulate economic growth and innovation. Circular economy initiatives drive economic development by creating jobs, attracting investment, and spurring innovation in resource-efficient technologies and business models [3].

Circular cities are inherently more resilient to fluctuating environmental conditions, resource constraints, and economic fluctuations. By diversifying resource flows, developing sustainable infrastructure, and adopting innovative solutions, circular cities can adapt and thrive in the face of challenges [4].

The central role of circular economy principles in urban planning lies in their ability to transform urban development towards sustainability and resilience. By adopting circular practices, cities can effectively address the challenges of waste generation and resource consumption while promoting environmental sustainability, economic growth, and urban resilience [4].

2 Methodology

The primary objective of this study is to examine and analyse the adoption of circular economy practices in urban planning in four cities: London, Amsterdam, Copenhagen, and Yokohama. The selection of the four cities, London, Amsterdam, Copenhagen, and Yokohama, for the case studies in this research, is justified based on their diverse and practical applications of circular economy strategies in urban planning. Each city has adopted unique approaches tailored to its specific context, but all are committed to achieving sustainability and resilience. The comparative analysis of these case studies allows for a comprehensive understanding of the different approaches taken by each city and their impact on sustainability and resilience in urban environments. The cities have been selected for their diversity in terms of economic, social, and environmental profiles. The selection criteria were based on the following factors:

- *Commitment to circularity.* The city should be committed to the circular economy and have implemented policies, programs, and initiatives to promote circular practices.
- *Progress in implementation.* The city should have made significant progress in implementing circular economy strategies and achieved measurable results in waste reduction, resource efficiency, and economic sustainability.
- *Innovation and leadership.* The city should lead in developing and implementing innovative circular economy solutions and serve as a model for other cities.

The study uses a mixed-methods approach, combining secondary data analysis and case studies. The case studies included an in-depth analysis of specific urban circular economy projects and initiatives in each city and interviews with crucial stakeholders involved in circular economy implementation. Qualitative data was also collected from secondary sources such as policy documents, reports, and government websites. The study found that the four cities have made significant progress in adopting circular economy practices.

3 Discussion

The four case studies presented in this study represent a variety of cities with different economic, social, and environmental contexts. Each city has its unique challenges and opportunities when it comes to implementing circular economy practices. However, all four cities are committed to sustainability and strive to create a more circular future.

These case studies demonstrate the diverse and practical applications of circular economy strategies in urban planning. Each city has adopted unique approaches tailored to its specific context, but all are committed to sustainability and resilience. By examining these case studies, valuable insights can be gained into how circular economy practices have been implemented in urban planning.

The comparative analysis of these case studies allows for a comprehensive understanding of the different approaches taken by each city and their impact on sustainability and resilience in urban environments.

The ultimate goal of this study is to promote the adoption of circular economy strategies in cities, leading to a more sustainable and resilient urban landscape. This study encourages and guides future urban development by highlighting successful examples of circular economy implementation, ensuring that cities are resource-efficient, liveable, equitable, and prosperous.

3.1 London, UK

London is a global leader in the transition to a circular economy, with several policies in place to promote resource efficiency and waste reduction.

The city has prioritised recycling and reuse, encouraging residents and businesses to participate in recycling programs and adopt circular practices [5]. The city has also focused on developing circular business models and supporting companies incorporating circularity into their operations. These initiatives aim to minimise waste generation and maximise the value of materials throughout their lifecycle.

In addition, London has been proactive in promoting circular design and manufacturing processes. By encouraging the development of products designed for durability, repairability, and recyclability, the city aims to extend the life of products and reduce resource consumption [6].

London's efforts to implement circular economy strategies align with its commitment to sustainability and resilience. The city aims to reduce its environmental impact, improve resource efficiency, and create a more sustainable future by adopting circular practices.

3.2 Amsterdam The Netherlands

Amsterdam is another city that has embraced the circular economy. The city has set an ambitious goal to become a fully circular city by 2050 and has implemented several initiatives to achieve this goal [7].

Amsterdam has established the Amsterdam Circular Innovation Program to support and accelerate circular startups and initiatives. The city provides funding, mentoring, and networking opportunities to innovative companies working on circular solutions through this program. In addition, Amsterdam has introduced the concept of the Amsterdam Circular Mile, a showcase of circular practices and businesses in the city centre [8]. This circular hotspot serves as a platform for collaboration, knowledge sharing, and inspiration, demonstrating the potential of circular economy principles in urban environments.

The city also focuses on promoting resource efficiency in buildings. Amsterdam encourages using sustainable materials, energy-efficient design, and circular construction practices [9]. The city aims to reduce waste and resource consumption by integrating circularity into the built environment while creating more sustainable and resilient structures [7].

Amsterdam's commitment to the circular economy is evident in its ambitious goals and comprehensive initiatives. By fostering circular startups, showcasing circular practices, and emphasising resource efficiency in buildings, the city is paving the way for a more sustainable and circular future [9].

3.3 Copenhagen, Denmark

Copenhagen is known for its strong commitment to sustainability and has made significant progress in implementing circular economy initiatives. The city has developed a comprehensive circular economy strategy encompassing waste management, sustainable construction, and renewable energy [10].

Copenhagen will become carbon neutral by 2025 and a zero-waste city by 2030. These goals reflect the city's determination to reduce environmental impact and create a more sustainable future [7].

Regarding waste management, Copenhagen has implemented innovative solutions to minimise waste generation and maximise resource recovery. The city encourages recycling and composting while promoting product reuse and repair. In addition, Copenhagen has implemented advanced waste-to-energy systems that convert non-recyclable waste into heat and electricity [10].

Sustainable construction is another crucial focus of Copenhagen's circular economy strategy. The city promotes using sustainable materials, energy-efficient design, and circular construction practices. By integrating circularity into the construction sector, Copenhagen aims to reduce resource consumption and waste throughout the lifecycle of buildings [7].

Copenhagen is also a leader in the use of renewable energy. The city has invested in wind power and district heating systems, significantly reducing its dependence on fossil fuels. By transitioning to renewable energy, Copenhagen contributes to the fight against climate change and promotes a more sustainable energy future.

Its comprehensive strategy and ambitious goals show Copenhagen's commitment to sustainability and circular economy principles. The city is working towards a more sustainable and resilient future by prioritising waste management, sustainable construction, and renewable energy [10]. Yokohama, Japan.

Yokohama is another city that has made significant progress in adopting circular economy principles. Recognising the circular economy's potential, the city has implemented several initiatives to promote energy efficiency, waste reduction, and sustainable transportation [11].

One notable initiative is the Yokohama Smart City Project, which integrates advanced technologies and sustainable practices into urban development. The project aims to improve energy efficiency, reduce waste generation, and enhance transportation systems. Through intelligent technologies and data-driven solutions, Yokohama is working to create a more sustainable and circular city [12].

Yokohama aims to become a model for a circular economy in Japan and beyond its borders. The city recognises the importance of transitioning to a more resource-efficient and sustainable development model. By embracing circular economy principles, Yokohama aims to minimise waste, maximise resource utilisation, and create a more resilient and livable city [11].

Yokohama's efforts to promote energy efficiency, waste reduction, and sustainable transportation are commendable and position the city as a leader in circular economy practices. By implementing innovative solutions and collaborating with stakeholders, Yokohama is paving the way for a more sustainable and circular future.

A summary table is provided to effectively compare and contrast the approaches taken by London, Amsterdam, Copenhagen, and Yokohama in adopting circular economy practices in urban planning. This table highlights each city's key projects, demonstrating the diversity and effectiveness of their urban circular economy initiatives (Table 1).

Table 1. Urban Circular Economy initiatives.

City	Project Name	Description
London, UK	The London Waste and Recycling Board [6]	The London Waste and Recycling Board delivers London's waste collection, treatment, and disposal services. The Board has set ambitious targets for waste reduction, aiming to divert 65% of waste from landfill by 2030
	London's Route Map to a Circular Economy [13]	London Waste and Recycling Board has developed a route map to guide the city towards a circular economy. This project explores local government strategies to facilitate circular development
Amsterdam, The Netherlands	City of Amsterdam Circular Economy Commitment [15]	The City of Amsterdam has committed to becoming a circular economy by 2050. The goal is to waste nothing and recycle everything
	Circular Office Park [16]	In Amsterdam, a circular office park was created as a test lab. This project, led by the Dutch circular economy specialist Metabolic, aims to explore and showcase circular economy principles in an office park setting
Copenhagen, Denmark	Circular Economy Strategy [10]	Copenhagen has developed a Circular Economy Strategy that outlines its goals and initiatives for achieving a circular economy. This strategy focuses on waste management, sustainable urban planning, and renewable energy leadership

(*continued*)

Table 1. (*continued*)

City	Project Name	Description
	Circular Copenhagen - Resource and Waste Management Plan 2024 [14]	Circular economy, recycling of resources, reuse. We use many different terms, but they all reflect the same: Much of what we call waste is resources. Furthermore, it is resources that we cannot afford to discard and destroy
Yokohama, Japan	Yokohama Blue Carbon [17]	A comprehensive initiative spearheaded by the Yokohama City Government to protect and restore the city's coastal ecosystems, particularly mangrove forests, seagrass meadows, and wetlands. These ecosystems are crucial in mitigating climate change by capturing and storing atmospheric carbon dioxide
	Yokoyoko Smart City Project [18]	The Yokohama City Government launched a comprehensive initiative 2016 to transform Yokohama into a "smart city" by leveraging advanced technologies to enhance urban life, improve citizen well-being, and address urban challenges

4 Results

The four cities discussed in this study have made significant progress in adopting urban circular economy principles. They have set ambitious goals, implemented comprehensive initiatives, and demonstrated the potential of circular economy strategies to create more sustainable and resilient urban environments. Their efforts provide valuable lessons for other cities seeking to transition to a circular economy.

This table provides a concise overview of the different approaches adopted by each city, highlighting their unique strengths and contributions to advancing circular economy principles in urban planning. The table serves as a valuable reference point for understanding the diversity of circular economy strategies and their potential application in different urban contexts (Table 2).

Table 2. Critical Elements of Circular Economy Strategies in London, Amsterdam, Copenhagen, and Yokohama.

City	Key Element	Description
London, UK	Waste Reduction and Resource Efficiency	Prioritising recycling and reuse, developing circular business models, promoting circular design and manufacturing processes
Amsterdam, The Netherlands	Green Infrastructure, Sustainable Mobility, and Circular Construction	Establishing the Amsterdam Circular Innovation Program, introducing the concept of the Amsterdam Circular Mile, promoting resource efficiency in buildings
Copenhagen, Denmark	Sustainable Consumption, Renewable Energy, and Circular Production Processes	Implementing innovative waste management solutions, prioritising sustainable construction, adopting renewable energy
Yokohama, Japan	Resource Recovery, Waste-to-Energy Conversion, and Circular Production Processes	The city focuses on resource recovery from waste streams, utilising waste-to-energy conversion technologies, and promoting circular production processes

5 Conclusion

The transition to a circular economy in urban planning offers a promising path toward sustainable and resilient cities. This study aims to provide valuable insights into implementing circular economy strategies and their potential benefits by examining successful case studies from different cities.

The comparative analysis of London, Amsterdam, Copenhagen, and Yokohama highlights the diversity of approaches and the need for a tailored approach to circularity in each city. However, common themes emerge, highlighting the importance of solid leadership, integrated planning, public-private partnerships, and community engagement.

The transformative power of the circular economy is highlighted, along with its potential to address pressing urban challenges and create sustainable and resilient cities for future generations. Embracing circular economy principles offers a promising path to a future of sustainability, economic prosperity, and environmental stewardship.

The case studies presented in this study provide valuable insights into how circular economy practices can be implemented in different urban contexts. By learning from the successes and challenges of these cities, we can accelerate the transition to a circular economy and create a more sustainable future for all.

The transition to a circular economy represents a transformative approach to urban planning, offering a pathway to sustainable and resilient cities. Analysis of the case studies of London, Amsterdam, Copenhagen, and Yokohama has revealed a rich tapestry of circular economy practices tailored to specific urban contexts. Each city is committed to resource optimisation, waste minimisation, and environmental stewardship.

London's focus on waste reduction and resource efficiency underscores the importance of upstream measures to reduce resource consumption. Amsterdam's emphasis on green infrastructure, sustainable mobility, and circular construction highlights the interconnectedness of urban systems and the need for holistic solutions. Copenhagen's prioritisation of sustainable consumption, renewable energy, and circular production processes demonstrates the potential of behavioural changes and technological advances to drive circularity. Yokohama's focus on resource recovery, waste-to-energy, and circular production processes reflects the importance of using waste streams as valuable resources.

These case studies exemplify how circular economy principles can be integrated into urban planning practices to promote sustainable and thriving urban environments. The diversity of approaches these cities take highlights the adaptability of circularity to different urban contexts and suggests that no single strategy is universally applicable. Instead, effective implementation of circularity requires careful consideration of local conditions, stakeholder engagement, and ongoing evaluation.

As cities worldwide grapple with resource scarcity, climate change, and environmental degradation, adopting circular economy practices in urban planning offers a compelling solution for achieving a sustainable and resilient future. The lessons learned from these case studies provide valuable insights for policymakers, urban planners, and citizens alike, enabling the widespread adoption of circularity principles to shape a more sustainable and harmonious relationship between cities and their environment.

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Circular Economy as a New Concept for Sustainable Building Development in Serbia

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Abstract. The concept of circular economy has become an important topic nowadays. This paper provides a brief literature review that introduces sustainability and the circular economy by presenting their origins and their conceptual definitions. In accordance with the above-mentioned, the standards applied in Serbia are enumerated. In April 2020, the Roadmap for Circular Economy in Serbia, the first document that initiated a dialogue between decisionmakers, industry representatives, academia and civil society in order to define the goals, future steps and a time frame for the transition from a traditional linear model to the circular economy, was adopted. In November 2020, Serbia accepted the conditions of the European Union for linking the European Green Deal with the strategic development of the region by signing the Green Agenda for the Western Balkans. Furthermore, Serbia has a Digital Platform for the Circular Economy that provides support to companies through business models, examples of good practice and tools, in order to more easily apply the circular business model, and reduce the carbon footprint in production processes and products. Although the implementation of the circular economy is at the very beginning, there are already several examples of good practice in Serbia, in terms of sustainable building materials.

Keywords: Circular Economy · Sustainability · Regulations · Green Agenda · Digital Platform

1 Introduction

Over the last 150 years, the worldwide industrial economies have been dominated by a linear economy (Fig. 1) – a traditional model of production and consumption in which goods are manufactured from raw materials, sold, used and then incinerated or discarded as waste [1]. Its application was mainly motivated by achieving profit regardless of the negative impact on the environment and natural resources. In this model of economy, after the end of the "lifetime" of the product, the same was disposed of in landfills for a long time, while with the increase in the exploitation of natural resources, there was also an increase in the amount of generated waste. More than 2.2 billion tons of waste are produced annually in the European Union. Therefore, its legislation on waste management promotes a shift to a more sustainable model known as the circular economy

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[2, 3]. In Serbia, the sectors of agriculture, forestry and fishing, mining, manufacturing, electricity, gas and steam supply, water supply and wastewater management, construction and service activities generated 56.3 million tons of waste just during 2020 [0]. Of the total amount of waste, even 20.1% was hazardous, while the rest was non-hazardous waste [0]. According to the Agency for Environmental Protection reports, the recycling of debris has not yet been established in Serbia, although 80% of construction waste can be recycled [4].

Fig. 1. Linear economy [5].

The concept of a circular economy is based on the assumption of using resources in the production and use in a way that maximizes the consumption period of the product, reduces the process of production and the amount of waste that cannot be reused, maximizes the utilization of resources, while, at the end of the cycle the product is returned to the production process in order to create new value [6]. The application of the circular economy requires greater investment in research to encourage the development of technologies that enable the application of this concept. In recent years, the concepts of circular economy and sustainability have increasingly gained traction in academia and industry, as well as among policymakers [7].

This paper presents a brief literature review that introduces sustainability and the circular economy by presenting their origins and their conceptual definitions. In accordance with the above-mentioned, the standards applied in Serbia are enumerated as well as several examples of good practice in the circular economy, in term of sustainable building materials. Furthermore, the existence of the Digital Platform for the Circular Economy [8] in Serbia is pointed out.

2 Sustainability

The term sustainability originates from the French verb *soutenir* which means "to hold up or support" [9]. Its modern conception has its origins in forestry because it is based on the silvicultural principle that was written down in the early 18th century in *Sylvicultura oeconomica* [10] and it states that the amount of wood harvesting should not exceed the volume that grows again. Afterward, the term sustainability (Fig. 2) was relocated to the context of ecology as a principle of respecting the ability of nature to regenerate itself [7, 11]. In the Oxford Dictionary of English [12] sustainable is defined as "able to be maintained at a certain rate or level".

Fig. 2. An example of a sustainability sign [13].

In 1987, when the World Commission on Environment and Development published its report "Our Common Future" (the Brundtland Report), the most commonly accepted definition of sustainability was given as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [7].

In 2017, after an extensive literature review, Geissdoerfer et al. [7] defined sustainability as a balanced integration of economic performance, social inclusiveness and environmental resilience for the benefit of current and future generations.

3 Circular Economy

The fundamental need for an alternative to the traditional linear economy led to the creation and development of the circular economy. The concept of the circular economy has been discussed since the late 1970s [7]. Its origins are mainly rooted in ecological [14] and environmental economics [15], and industrial ecology [16]. Based on the Boulding's idea [14], environmental economists Pearce and Turner [15] primarily introduced the concept of a circular economic system. With the enactment of the "Closed Substance Cycle and Waste Management Act" in 1996, Germany became a pioneer in integrating the circular economy into national laws [17], followed by Japan's 2002 "Basic Law for Establishing a Recycling-Based Society" [18], and China's 2009 "Circular Economy Promotion Law of the People's Republic of China" [19]. Even supranational bodies have also incorporated circular economy concerns, e.g. via the EU's 2015 Circular Economy Strategy [20].

There is not just one, but many definitions that are used in parallel for circular economy. According to Ellen MacArthur Foundation, recent theories related to the circular economy are constantly evolving the concept itself. One of the most recognized definitions of the circular economy was proved by the Ellen MacArthur Foundation and that is: "A circular economy is one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles." [21].

At the international standardization level, the circular economy is defined as "An economy that is restorative and regenerative by design, and aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological cycles." [22].

In 2017, after an extensive literature review, Geissdoerfer et al. [7] defined the circular economy as a regenerative system in which resource input and waste, emission as well as energy leakage are minimized by slowing, closing, and narrowing material and energy loops. The above-mentioned can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing and recycling. Therefore, the circular economy is viewed as a condition for sustainability, a beneficial relation or a trade-off.

In practice, the application of the circular economy extends the life cycle of products, while the amount of waste is reduced to a minimum, (Fig. 3).

Fig. 3. A circular economy model that implies less consumption of raw materials, less residual waste and less emissions [2, 3].

4 Law in Serbia

The Ministry of Environmental Protection and the Circular Economy United Nations Development Program participated in the drafting of the document Roadmap for Circular Economy in Serbia [4] that was adopted back in April 2020 [0]. The Roadmap represents the first document that initiated a dialogue between decisionmakers, industry representatives, academia and civil society in order to define the goals, future steps and time frame for the transition from the traditional linear model to the circular economy [0].

In November 2020 [0], Serbia accepted the conditions of the European Union for linking the European Green Deal with the strategic development of the region by signing the Green Agenda for the Western Balkans [23]. The Agenda represents the blueprint for a 2050 future of climate neutrality and environmental sustainability. Furthermore, it is aligned with the ambitions of the European Green Deal and relies on urgent regulatory reforms and significant investments. The five main pillars of the Agenda [24] are:

- Decarbonization and climate resilience,
- Circular economy,
- Depollution: air, water and soil,
- Sustainable food systems and rural areas,
- Biodiversity: protection and restoration of ecosystems.

The Economic and Investment Plan promotes the implementation of the Agenda through the following four flagships (that extend over one or more pillars):

- Environment and climate,
- Clean energy,
- Sustainable transport,
- Private sector development.

This Plan represents a financial mechanism for accelerating the Green Agenda for the Western Balkans through green and digital transition, as well as fostering regional cooperation and convergence with the European Union [0]. Furthermore, the following ten flagships are identified as key indicators of a successful transition by this Plan: Connecting East to West, Connecting North to South, Connecting the coastal region, Renewable energy, Transition from coal, Renovation wave, Waste and waste water management, Digital infrastructure, Investing in the competitiveness of the private sector, and Youth guarantee.

Although Serbia adopted the Law on Waste Management [25] in 2009, the Regulation on the Manner and Procedure of Waste Management from Construction and Demolition [26] was adopted a few months ago, in October 2023. The ISO 20887 [27] which deals with sustainability in buildings and civil engineering works in terms of the design for disassembly and adaptability was published back in January 2020.

Given that the European Union has set a recycling goal of 55% by 2025 [0], it is necessary to point out the lack of recycling capacity and adequate waste disposal in Serbia. Therefore, Serbia has committed itself to supporting the construction sector in the development of construction and demolition waste management systems, as well as the recycling sector to improve recycling processes for certain waste streams in relation to substances that cause concern [28]. The following standards relating to recycled aggregate are applied in Serbia:

SRPS EN 206:2021 Concrete - Specification, performance, production and conformity [29],

- SRPS EN 12620:2010 Aggregates for concrete. [30],
- SRPS EN 13055:2017 Lightweight aggregates. [31],
- SRPS EN 933 series of standards: Tests for geometrical properties of aggregates. Part 1 (2013) [32], Part 2 (2021) [33], Part 3 (2013) [34], Part 4 (2010) [35], Part 5 (2023) [36], Part 6 (2023) [37], Part 7 (2007) [38], Part 8 (2016) [39], Part 9 (2023) [40] and Part 10 (2009) [41], while Part 11 (2020) [42] is deleted from the standards committee’s work plan.

On September, 29, 2023, SRPS EN 197-6:2023 Cement - Part 6: Cement with recycled building materials was published [43].

Serbia also has Regulations on Energy Efficiency of Buildings [44], and Regulations on Conditions Content and Method of Issuing Certificates on the Energy Performance of Buildings [45].

While the standards referred to the circular economy are in the phase of consideration and adoption of suggestions and comments of interested parties, intending to improve their content, the following International Standards in Circular Economy are applied in Serbia:

- ISO/FDIS 59004:2023 Circular Economy - Terminology, Principles and Guidance for Implementation. [46] Effective date: December 13, 2023,
- ISO/DIS 59010:2023 Circular Economy - Guidance on the transition of business models and value networks. [47] Effective date: October 4, 2023,
- ISO/FDIS 59020 Circular Economy - Measuring and assessing circularity performance. [48] Effective date: December 11, 2023.

Furthermore, Serbian Chamber of Commerce, United Nations Development Programme and the German Organization for International Cooperation founded the Digital Platform for the Circular Economy [8] that provides support to companies through business models, examples of good practice and tools in order to more easily apply the circular business model, and reduce the carbon footprint in production processes and products.

5 Examples of Good Practice in Serbia

Construction is one of the preliminarily identified priority sectors in Serbia, besides the manufacturing industry, agriculture and food, and plastics and packaging, that is selected based on the possibility of fast and adequate implementation of the concept of circular economy business models, by efficient use of the raw materials, increasing the value of used materials, mobilizing the use of circular economy business models for products and services, promoting energy efficiency, closing the loop in the use of materials, preventing waste generation, implementing green public procurement, and developing the circular culture in the general society [4].

An example of the good practice from the construction sector in Serbia comes from Company FEPLO, which produces waterproof eco-panels using carton packaging from municipal and packaging waste with a 10% addition of mouldable polymers instead of glue [4]. The panels are used as construction material for rooftops and floor structures, and can be used as an alternative to wooden products that fulfill the same role. Furthermore, new buildings have energy passports as well as existing buildings that are being reconstructed, extended, restored, adapted, rehabilitated, sold, leased, or energetically rehabilitated. Also, the cement industry (e.g. Lafarge BFC, located in Beočin) uses by-products (e.g. ground granulated blast-furnace slag and fly ash) from other industries for the production of certain types of cement. Ground-granulated blast furnace slag represents a by-product of iron and steel production. There is only one steel production conglomerate in Serbia - HBIS GROUP Serbia Iron & Steel, located in Smederevo. Fly ash is a by-product created in thermal power plants that utilize pulverized coal as a fuel source. Annually, about 40 million tons of low-calorie lignite (from the Kolubara and Kostolac coal basins) are burned in thermal power plants in Serbia, resulting in about 6 million tons of fly ash and slag. Up to now, around 200 million tons of the mentioned by-products have been disposed of in landfills with an area of 1,500 hectares [49, 50]. Ground-granulated blast furnace slag and fly ash are also used as a partial replacement of ordinary Portland cement in mortar or concrete production, i.e. as type II addition in accordance with standard SRPS EN 206:2021 [51].

6 Conclusion

Based on a brief review of the literature in terms of circular economy and sustainability, as well as the laws in force in Serbia, and examples from practice, the following conclusions can be drawn:

- Recently, both the circular economy and sustainability have increasingly gained traction among academia, industry and policymakers.
- In April 2020, the Roadmap for Circular Economy in Serbia was adopted, while in November 2020, Serbia accepted the conditions of the European Union for linking the European Green Deal with the strategic development of the region by signing the Green Agenda for the Western Balkans.
- While the standards referred to the circular economy are in the phase of consideration and adoption of suggestions and comments of interested parties, intending to improve their content, the International Standards in Circular Economy are applied in Serbia.
- Serbia is at the very beginning when it comes to the application of the circular economy, but there are already several examples of good practice in the construction sector.
- The establishment of the Digital Platform for the Circular Economy has a significant role in raising awareness of the circular economy importance among industries and companies through the Serbian Chamber of Commerce, which is one of its co-founder.

In general, Serbia should considerably step up its ambitions towards a green transition and focus on ensuring strict compliance with environmental impact assessment rules, increasing investment in waste reduction, as well as separation and recycling.

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Environmental Impact of Circularity Strategies and Solutions

Decarbonization Possibilities for Affordable Timber Houses. An LCA Comparison of Business as Usual and Circular Strategies

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Abstract. To better understand the full impact of building materials and buildings over their lifetime and beyond, Lifecycle Assessment (LCA) studies have been an area of interest and a growing body of knowledge. Moreover, recent studies emphasize the critical importance of the end-of-life (EoL) scenario, particularly for wood-based construction, and highlight its potential for further decarbonization through circular strategies. However, there is a significant knowledge gap in the LCA literature regarding mitigation strategies specific to affordable housing options, despite the urgent and undeniable need for these typologies worldwide. This study contributes to filling this gap by conducting a materials-level, whole-building LCA of a prototype affordable single-family house built in 2020 using a business-as-usual wood-frame construction method. Besides the conventional as-built scenario, this study developed five hypothetical scenarios that evaluated the influence of different EoL options (recycling or energy recovery), enhanced circular strategies (reduce and reuse), and substitution of non-renewable materials with circular materials for insulation (wood fiber) and finishing (clay plaster), with the aim of identifying further opportunities and limitations for decarbonizing such a typology and construction method. The results of this study consistently indicated that the order of priority should be to (1) ensure appropriate end-of-life for metals and wood-based materials. (2) Replace non-renewable materials with renewable wood or earth-based materials. (3) Improve material reuse and construction waste diversion rates. The results of the study could support decision-making processes for the design and construction of low-impact affordable single-family homes and the development and implementation of affordable housing policies and regulations.

Keywords: Affordable Housing · LCA · Wood frame · Circularity · Circular economy · Light Wood Framing

1 Introduction

The construction sector is responsible for the largest individual share of greenhouse gas (GHG) emissions, accounting for 37% of all emissions [1], due to energy-intensive activities of material extraction, transportation, construction, and energy to operate buildings.

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Building construction activities alone represent 10% of all emissions [1]. Hence, the high emissions in the sector worsen the continual warming of the planet and contribute to the climate crisis. Moreover, the construction industry consumes 40% of the global resources [2] and is one of the leading producers of solid waste generated during the production of materials, construction, and demolition of buildings [3]. That means a large share of emission-intensive building materials produced from precious finite resources end up in landfills as a result of manufacturing, construction or demolition activities.

Given the remarkable influence of the construction sector and aiming at a better understanding and evaluation of the full impact of building materials and buildings over their service time, life cycle assessment (LCA) studies have been a field of interest and growing body of knowledge over the past three decade, finding significant differences between common building materials such as steel, concrete or wood [4] and highlighted the crucial role of wood products' energy recovery at the end-of-life (EoL) to mitigate impacts. Previous studies [5–7] by the author of this paper also support the critical role of EoL to mitigate the environmental impact of construction.

In particular, understanding the embodied emissions of materials in a building is paramount to reducing the impacts of the construction sector [8], as it can contribute from 10% to 50% of the total lifecycle GHG emissions, depending on how energy-efficient a building is [9]. However, despite its relevance, Cai [10] warns of a still limited number of studies reporting material-level embodied impacts, which can lead to underestimation. Moreover, recent papers stress the central relevance of materials' EoL scenario and its further potential for impact mitigation by extending the lifespan of buildings and service times of materials through circular strategies such as design for adaptability, disassembly, and reuse [11, 12].

However, after a broad review of available LCA literature over the past 20 years, analyzing more than 230 published papers, Bahramian [13] showed a tendency for LCA to focus on low-rise commercial buildings in the USA, with only one study about a low-rise house. It was also noteworthy in the literature review the almost complete absence of studies about affordable/social housing options, with only two papers on the topic originating from Latin America. Despite this noticeable scientific gap, there is a pressing and undeniable need for more affordable houses, also in North America.

Hence, understanding the embodied environmental impact of building materials and methods suitable for affordable housing must also be an integral topic of scientific investigation. This study addresses the identified scientific gap related to the lifecycle impact investigation of a single-family home for the affordable market in the southern U.S. This study builds on the initial findings of [7], which identified lightweight wood framing as the most promising option for reducing the environmental impact of single-family homes in the South, by increasing the sample size of such a construction system to seek new insights and verify the results. Thus, it aims to contribute to the field with original information on the environmental performance of affordable housing building options that facilitates decision-making processes, leading to new knowledge that can support the design and construction of lower-embodied-impact affordable single-family homes in the south of the USA.

2 Methods

2.1 LCA Scope

This study conducted an LCA as per EN-15804 (Table 1) of one affordable single-family house (91.69 m^2) built in 2020 using light wood framing in the southern U.S. (Fig. 1). The study calculated the global warming potential (GWP) of the as-built house and developed hypothetical scenarios including increased circular strategies and regenerative materials use (item 2.2) to evaluate further possibilities and limitations for impact mitigation.

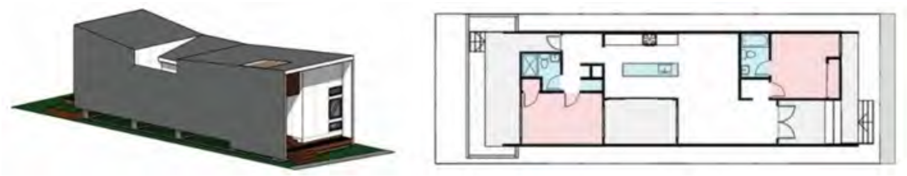

Fig. 1. Case study: massing strategy (left); floor plan (right).

Table 1. LCA Phases and modules assessed per EN-15804 standard.

Stages	Modules	Assessment
Product	A1 - Raw material supply	Yes
	A2 - Transportation	Yes
	A3 - Manufacturing	Yes
Construction	A4 - Transportation	Yes
	A5 - Construction	Yes
Use	B1 - Installed product in use	No
	B2 - Maintenance	Yes
	B3 - Repair*	Yes
	B4 - Replacement	Yes
	B5 - Refurbishment	No
	B6 - Operational energy use	No
	B7 - Operational water use	No
End-of-life	C1 - De-construction/ demolition	Yes
	C2 - Transportation	Yes
	C3 - Waste Processing	No
	C4 - Disposal	Yes
Benefits and loads beyond boundary	D - Reuse, Recovery, Recycle	Yes

* According to the repair schedule from [7]

Using the as-built construction documentation of the case-study house, a detailed bill of materials (BOM) was defined (Table 2). Then, lifecycle inventory data for each specified material was gathered from the Athena Sustainable Materials Institute database [14], which provides ISO 14040/14044-compliant data. The database is geographically adjusted to reflect the industry-wide national average values in the USA and regularly updated to account for the latest manufacturing technology, transportation requirements, and energy mix context, with data less than ten years old. At the time of this writing, three building materials were still unavailable in the database (item 2.2). Nonetheless, the impact data on these three materials was also retrieved from ISO-compliant Type III EPDs. After gathering all LCI data, the Impact Estimator for Buildings software (IE4B v.5.4.0101) was used to obtain the lifecycle impact assessment (LCIA) values for a functional unit of 1 m^2 of construction and a 60-year lifespan.

Table 2. Bill of materials (BOM) in kg/m^2.

Role	Material	Waste	Mass
Foundation	RC footings	5%	388.19
Foundation	CMU pier	6%	4.89
Structure/Envelope	Kiln dried softwood	8%	88.40
Structure/Envelope	Subfloor – OSB	5%	10.96
Structure/Envelope	OSB	5%	30.41
Structure/Envelope	Galvanized steel fasteners	3%	1.69
Structure/Envelope	Insulation – Rockwool	5%	16.28
Structure/Envelope	Double Glazing (Hard coat, Air fill)	0%	24.13
Structure/Envelope	Door Panel – Plywood	0%	0.55
Structure/Envelope	Window frame - aluminum	0%	0.36
Finishing	Airtight membrane	2%	1.63
Finishing	Water-poof bituminous membrane	2%	0.60
Finishing	Galvalume corrugated roof sheet	5%	7.72
Finishing	Gypsum plasterboard	10%	40.89
Finishing	Fiber cement board	10%	6.49
Finishing‘	Paint - Latex	2%	7.17
Finishing	Paint - Acrylic	2%	6.22
Finishing	Ceramic Tiles (wet areas)	10%	13.34

2.2 LCA Scenarios

This study assessed six scenarios to understand the possibilities and limitations for further impact mitigation, described in the sequence. Table 3 presents an outline of each scenario and the assessed variable within each one of them.

Standard Scenarios. *S1:* This scenario represents the standard LCA of the as-built case-study. Therefore, it provides a benchmark for the study, with a conventional optimistic view of material recovering and recycling at the end of life. *S2:* This scenario investigates a conceivable pessimist end-of-life fate for sawn wood and metals (aluminum, and galvalume sheathing), typically assumed to be recycled or incinerated for energy. This scenario considers that only half of these materials would be soundly recycled or incinerated due to the likely challenges of sorting after a conventional demolition process of such buildings [15, 16]. Hence, it estimates the influence of the standard end-of-life fate on the overall LCA results by reducing the benefits obtained in module D. To account for the uncertain effect of different recycling ratios within our scenario, the author performed a sensitivity analysis (±50%).

Circular Strategies. *C1:* This scenario investigates the effect of reducing construction waste below the national average through off-site prefabrication. According to previous studies [17, 18], off-site prefabrication can reduce construction waste by up to 40% of the on-site values due to a more controlled manufacturing environment. Therefore, the author accounted for the potential benefits of construction waste reduction by decreasing the waste amount by a factor of 2.5. To account for the uncertain effect of different waste ratios within our scenario, the author performed a sensitivity analysis (±50%). *C2:* This scenario investigates the effect of reusing wood and metal building materials in construction. The author assumed a conservative 50% reuse ratio for sawn wood [16, 19] and metals (aluminum, and galvalume sheathing). That allows this scenario to measure the benefits of reuse compared to the conventional EoL fate of energy recovery and recycling in S1. The benefits of reuse were allocated to Module D as the avoided burden of producing new materials from the cradle, as per closed material loop allocation methodology (ISO 14044:2006 section 4.3.4.3.3). To account for the uncertain effect of different reuse ratios within our scenario, the author performed a sensitivity analysis (±50%).

Regenerative Materials. *M1:* This scenario evaluated the effect of replacing the most impactful envelope material in S1 with a functionally equivalent regenerative material. The GWP results per material showed the highest impacts in S1 arise from glass followed by insulation. The latter material was replaced with wood fiber insulation because there is no regenerative option for glass on the market yet. *M2:* This scenario evaluated the effect of replacing the most impactful finishing material in S1 with functionally equivalent regenerative materials. The GWP results per material showed the highest impacts arise from the galvalume roof sheathing followed by paints. The latter material was replaced with clay plaster applied on the gypsum plasterboard, following the specifications of the manufacturer [20], because there is no functionally equivalent regenerative option for galvalume sheathing on the market yet.

Table 3. Description of modified parameters assessed in each scenario.

Scenarios	Condition	Waste	Recycle	Reuse	Replacement
S1 – Standard	Optimistic	Avg	Yes (1)	No	No
S2 – Standard	Pessimistic	Avg	50% (1)	No	No
C1 – Circular	Reduce	40%	Yes (1)	No	No
C2 – Circular	Reuse	Avg	Yes (1)	50% (1)	No
M1 – Regenerative	Envelope	Avg	Yes (1)	No	Yes (2)
M2 – Regenerative	Finishing	Avg	Yes (1)	No	Yes (3)
(1) Wood and metals; (2) Insulation; (3) Paints					

3 Results and Discussion

3.1 Aggregated LCA Results

The aggregated results (Fig. 2) showed that S2 has the highest GWP value of all scenarios, while S1came in third. That attests to the high relevance of a pessimistic yet plausible EoL scenario on the environmental performance of light wood framing affordable houses. Contrarily, C2 is the second most impactful scenario, showing a more limited mitigation potential of reusing materials. However, for reuse (C2), it is worth noting that the reduced mitigation potential from reuse derives from a smaller amount of wood available at the end of life, thus reducing the benefits at module D and increasing GWP values. That is a methodological issue within the cradle-to-grave approach of a static LCA. S1, C1, and M1 scenarios display minor variation with a mean of 1.5%. C1 was the least impactful of the three, indicating a preference for reducing material waste to mitigate impacts, compared to replacing rock wool insulation with wood fiber. Finally, M2 achieved the lowest GWP value, demonstrating the high environmental costs that a conventional painted finish can have on light wood framing houses and the potential of clay plaster as a mitigation alternative.

3.2 LCA Results by Construction Role

Figure 3 shows that the finishing materials account for the highest share of GWP regardless of the scenario. For most scenarios, the foundations were the second-most impactful part of construction, followed by the envelope in third place. The impact of finishing materials was virtually the same for S1, S2, M1, and C2, with a mean variation of 0.25%, indicating a minor mitigation potential of reusing the finishing materials of the case study. The GWP of finishing materials in C1 was slightly below the mentioned scenarios (−2.5%) due to a lower construction waste rate, which shows the relevance, although limited, of the implementing measures that increase material efficiency during the construction phase. The GWP of finishing materials in M2 was the lowest, circa 71% lower than S1, because of the replacement of latex and acrylic paint finishing with clay plaster. As for envelope materials, S2 showed the highest GWP, followed by C2

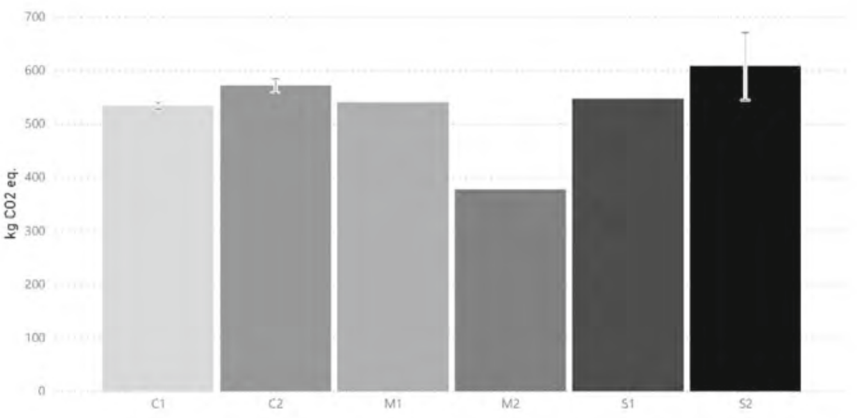

Fig. 2. Total embodied Global Warming Potential (GWP) by scenario.

with 200% and 143% more impact than S1, respectively. That reiterates the critical need for a suitable EoL of materials and limited mitigation potential of reusing materials and measuring its benefits in a cradle-to-grave LCA model. S1, C1, and M2 showed the lowest GWP values, demonstrating the effectiveness of guaranteeing a suitable EoL for materials, reducing construction waste below the average, and using regenerative finishing materials, respectively. M1 presented the lowest GWP value for the envelope, 10.3% lower than S1, attesting the benefits of using wood fiber insulation as a replacement for rock wool.

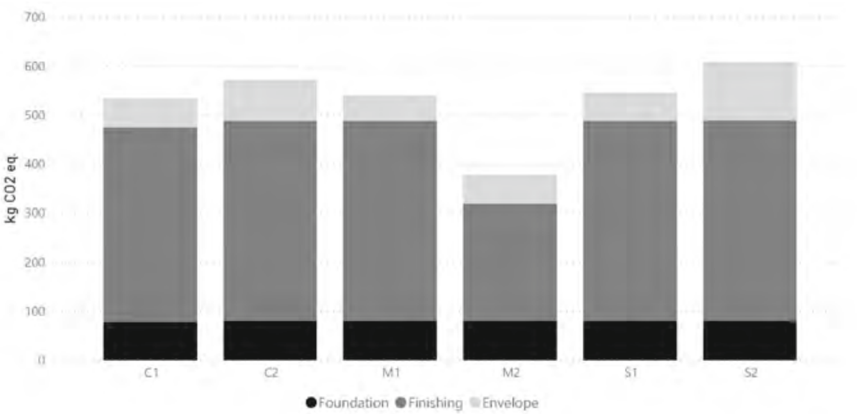

Fig. 3. Embodied Global Warming Potential by construction role.

4 Conclusions

This study conducted an LCA study of one affordable single-family house built in 2020 using light wood framing in the southern U.S. The study calculated the GWP of the as-built house and developed five hypothetical scenarios, including increased circular strategies and regenerative materials use.

The Standard Scenarios result showed suitable EoL handling of materials, namely recycling of metals and recovery of wood-based materials, has a significant mitigation impact on GWP compared to the pessimistic scenario where only half of these materials would be recycled or recovered due to the possible challenges of material sorting after a conventional demolition process of such construction system, consisting predominantly of nailed connections. The first circular scenario of reducing construction waste below the national average showed a small but sure potential to lower the GWP; the second circular scenario of reusing metals and wood-based materials increased the impact compared to the standard scenario due to the reduced availability of wood to be recovered and converted into energy at the end of life, thus reducing the benefits at module D. Moreover, replacing mineral wool with wood fiber insulation in the first regenerative scenario showed a limited mitigation potential. However, replacing latex and acrylic paints with clay plaster reduced the GWP of the case study by a large margin, demonstrating the high environmental costs that a conventional painted finish can have on light wood framing houses.

To sum up, the results indicate that increased use of circular strategies and regenerative materials offered further mitigation and decarbonization potential for the light wood frame affordable single-family house case study. Throughout this study, results pointed out that priorities should be to (1) guarantee proper end-of-life of metals and wood-based materials. (2) To replace non-renewable materials with regenerative wood or earth-based ones. Lastly, (3) to improve construction waste diversion rates. This study assessed one case of a light wood framed affordable house. Therefore, more case studies under the same circumstances should be assessed to validate the results as general design guidelines. Additional topics that were out of scope but can tackled in further research could include 1) investigating the real-life challenges and possibilities of design for the disassembly, recovery, and reuse of lightweight construction methods. 2) Developing LCA studies that assess a broader range of regenerative materials for structural, insulating, and finishing roles in an affordable house. 3) Evaluating the financial impacts of incorporating novel regenerative materials in affordable single-family homes built with lightweight construction methods.

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Life Cycle Assessment and Sustainability Characteristics of Built Environment Systems

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Abstract. The sustainable built environment concept has recently gained enormous attention from academic and industrial organizations. The growth in climate-related disasters and pandemics, continuing difficulties in the energy sector, and consumer awareness regarding resources' conservation and sustainability are considered the driving factors influencing participants toward supporting sustainable engineering applications. Furthermore, numerous professional standards and requirements for implementing and rating sustainable practices have been generated, such as life cycle assessment (LCA), cost analysis, project development (i.e., from planning through construction up to demolition), recycling, material preservation, and utilizing reusable materials. The LCA is a great method for examining and integrating a wide variety of environmental elements to provide a comprehensive picture of system sustainability. The research presented in this study covered significant environmental elements that are essential to deciding between two or more choices and improving the system. This research compared the OPC and AABC based on CO_2 emissions. The results showed that the AABC produces positive sustainability outcomes in terms of CO_2 emissions. The AABC emits substantially less CO_2 than the OPC, indicating that it is preferable for greenhouse buildings.

Keywords: Built Environment · Sustainability · LCA · CO_2 emissions

1 Introduction

In developing communities with limited resources, resilience and sustainability are crucial components for creating high-performance infrastructure [1, 2]. Prior to the 19th century, the concept of resilience as a design principle was inherent in common construction knowledge. Buildings' resilience was increased through implicit construction knowledge such as oversizing of parts and spaces, redundancy, and reparability. One of the most important factors of sustainability is the life cycle assessment (LCA) of the built environment systems, which analyzes the environmental impact based on the phases of manufacture and production, usage, and destruction. The LCA is divided into

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four phases: scope definition and aim, analysis of inventory, impact evaluation, and interpretation [3, 4]. The LCA can be used to determine durability, mechanical strength, cost, energy, and emissions criteria. By providing a complete picture of the required energy and CO_2 emissions, this technique allows a thorough comparison of transit, material production, usage, and demolition implications [5, 6]. The life cycle stages for the manufacture of material feedstocks, which include collection, transporting, mining, and calcining of these feedstocks, are examined first, followed by the manufacturing process, including mixing these raw materials [7–10]. The availability of sources is also an important factor in sustainability; it has a key impact on the cost, which includes the stages of the excavating process, including extracting, transporting, forming, and construction time. Therefore, the high availability of sources activates the construction process and shortens the project's duration to minimize purchasing effort and human potential in the alternative search [11, 12]. Furthermore, the use of waste materials from finished projects or demolished structures as recyclable materials has a good impact on the built environment, with the goal of reducing waste materials in landfill areas and using available materials [13, 14]. The availability of building materials is considered a criterion of embodied energy in selecting materials. Furthermore, in order to achieve environmental protection and decrease gas emissions during excavation and transportation, it is preferable to utilize locally available materials for the project instead of the materials available in remote areas that need time and financial potential for transportation, even if the project location is remote. Therefore, employing easily accessible building materials improves sustainability by reducing the possibility of excavation, expense, gas emissions, working time, human potential, and embodied energy [15, 16]. Despite its significance for the sustainability of built-environment systems, resilience is not explicitly considered by studies of LCA. Resilience is a design principle that is associated with a combination of sustainability and the ability to recover in the shortest time. This term becomes more tangible when unexpected disasters happen in urban infrastructure, particularly in residential buildings [17, 18]. Resilience refers to the capacity of buildings, infrastructure, and communities to endure and recover from a variety of shocks and stresses, including climate change, natural disasters, and other disruptions. Thus, resilience is a key factor in the built environment because it can mitigate the effects of climate change, reduce loss and damage, promote sustainability, and ensure long-term viability and economic stability [19, 20]. The principal objective of this paper is to investigate the techniques for monitoring resilient and sustainable construction projects and resolving difficulties and possibilities in the long-term development of resilient built-environment systems.

2 Built Environment Sustainability

The sustainable built environment system, also known as the sustainable ecosystem, can be defined as a complicated and integrated system of natural resources, processes, and elements that work together to minimize adverse environmental effects while preserving ecological balance and providing necessary services to support life on Earth. The created or man-made environments in which individuals live, work, and interact are referred to as the built environment system. It includes all of the physical features, such as gardens, roads, bridges, buildings, and other services, that comprise both urban and rural regions.

This system is an important part of human civilization and has a major influence on the environment, economic growth, and standard of living. A sustainable environment system has the following essential elements: resource conservation, which includes the utilization of natural resources such as atmosphere, water, land, energy, material, and biodiversity (i.e., a wide variety of species); cost efficiency of the constructed projects in all stages (i.e., initial cost, cost in use, and recovery cost); and design for human adaptation, which could include the minimization of production waste, keeping water and air clean, and protecting human interaction with the environment [21, 22]. A schematic representation of the built-environment system is displayed in Fig. 1.

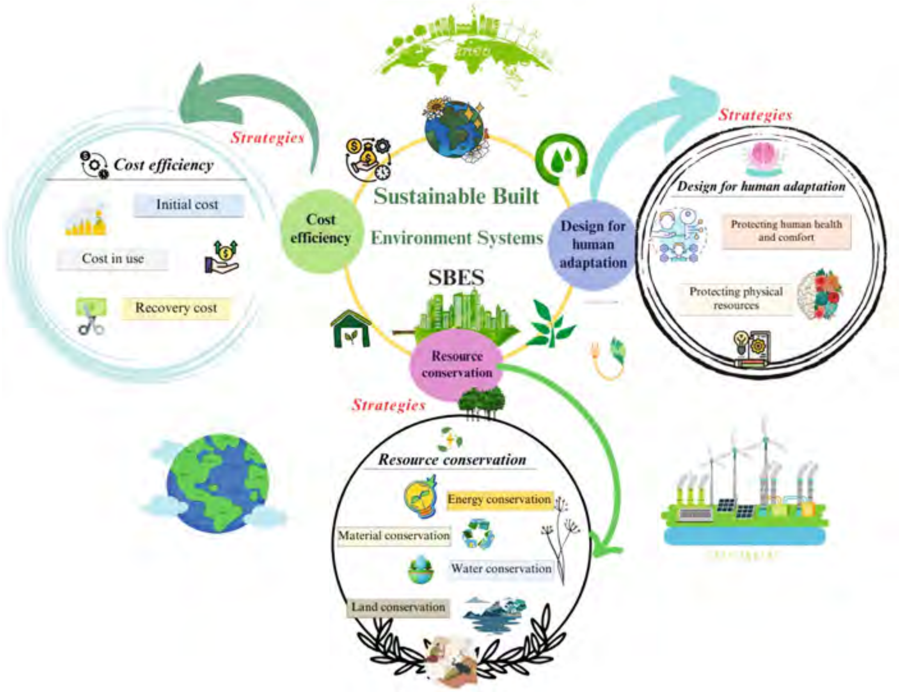

Fig. 1. Sustainable built environment system (SBES).

The built environment system can be assessed using the meaning of the LCA of the used materials (e.g., cement, ordinary concrete, geopolymer concrete, steel, asphalt, masonry, etc.), especially in construction projects (i.e., buildings, roads, bridges, tunnels, dams, etc.). The impact of various factors such as sustainability, resilience, available opportunities, challenges, and LCA on the built environment systems is described in detail in the following subsection. The conceptualization of resilience has developed over the past decade and is frequently discussed alongside the concept of sustainability. As a result, because both of these ideas come together and are utilized simultaneously, they must be considered jointly. The philosophy of sustainability, and subsequently resilience, is part of a broader narrative that has affected a wide range of specific topics and geographic situations, including metropolitan regions. Resilience is being utilized more and more to understand extremely complex, dynamic social systems, such as metropolitan regions. This may shed light on difficult concepts related to sustainability and resilience [22–24].

3 Life Cycle Assessment (LCA)

The LCA is a unique tool that comprises all procedures and environmental releases, from the extraction of raw materials and the production of energy necessary to manufacture the product to its usage and final disposal. The LCA considers a wide range of environmental aspects, including energy use, resource consumption, and emissions, to provide a comprehensive view of a product's sustainability. Thus, the LCA can assist decision-makers in comparing all key environmental impacts generated by products, processes, or services when choosing between two or more alternatives [25]. The LCA usually examines how building materials affect the environment by considering various aspects, including resource extraction, manufacture, transportation, and disposal at the end of the product's life. It evaluates these materials' embodied energy, carbon footprint, and environmental metrics. The LCA considers energy and emissions, which are related to site work, and evaluates the use of energy and resources during building operations [26, 27]. The LCA can also examine building demolition and disposal, which include investigating the environmental impacts of waste management, demolition, and potential material recycling or re-use. The LCA frequently examines a building's whole life cycle, from cradle to grave, and considers a variety of environmental indicators, including carbon emissions, energy consumption, and water use, to thoroughly assess the sustainable built environment system (Fig. 2).

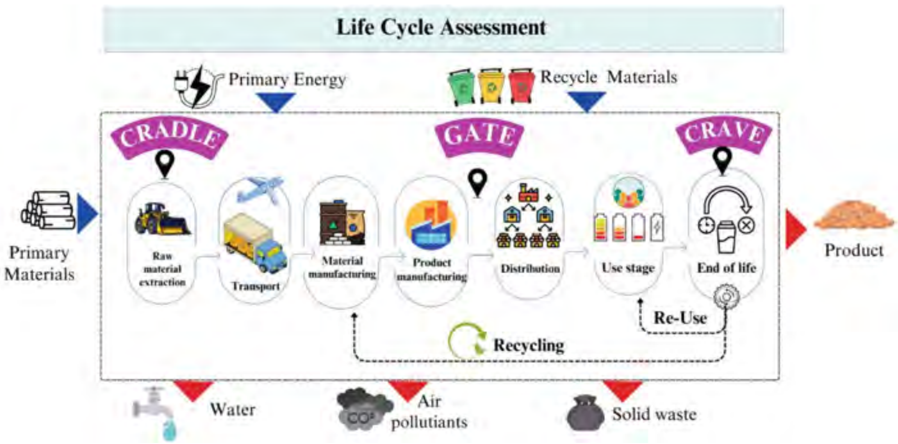

Fig. 2. Typical architecture of the LCA application in civil engineering.

4 Materials and Methods

In general, applying the concept of LCA to a domestic zone can assist legislators, engineers, urban planners, architects, and developers in making choices that avoid negative environmental consequences. The tool used to apply the environmental assessment for the whole framework in this paper is CO_2 emissions. In order to apply the LCA for assessing a built environment framework, a virtual system of a compound city was taken as an example to compare the CO_2 emissions values of a city built using ordinary Portland cement (OPC) concrete and another city built using alkali activated binder (AABC) concrete. Various types of buildings were included in the study for a good evaluation of the environmental impact, and the construction site works (i.e., infrastructure works) were also included in the study data estimation. The city (i.e., compound) consists of ten 4-floor residential buildings, five 2-floor villas, four 4-floor commercial buildings, two 3-floor schools, one language center, and two 2-floor health centers. The details of each building type (i.e., number of buildings, area of each building, and total area) are listed in Table 1. A schematic representation of the studied compound with all building types is displayed in Fig. 3. The data used in the LCA analysis for various building types and two concrete types (OPC and AABC) were collected from reputable published research studies [6, 28, 29] and then applied to the constructed virtual compound. A comparison between the OPC and AABC was produced by creating each concrete type's life cycle stages and then computing its CO_2 emissions. The numbers shown in Table 2 represent the amount of CO_2 emissions resulting from casting 1 m^2 of the building area using either OPC or AABC, the total amount of CO_2 emissions, and the percentage of CO_2 emissions. It can be observed that the CO_2 emissions using the AABC are significantly lower than the OPC, which attests that the use of the AABC is desirable in greenhouse construction. According to Fig. 4, the total CO_2 emissions resulting from residential buildings are the highest, since the majority of buildings in a typical built environment are residential buildings.

Fig. 3. 3D plan of the virtual compound.

Table 1. The details of each building type.

Building type	Number	Area (m^2)	Total area (m^2)
4-floor residential building	10	1600	16000
2-floor Villa	5	500	2500
4-floor commercial building	2	500	1000
3-floor school	2	4500	9000
Language center	1	2500	2500
2-floor health center	2	1000	2000
Construction site works	1	18500	18500
Sum			51500

Table 2. LCA results for the various buildings and concrete types.

Concrete	OPC			AABC		
Building	CO_2 emissions (kg/m^2)	Total CO_2 emissions (kg)	Total CO_2 emissions (%)	CO_2 emissions (kg/m^2)	Total CO_2 emissions (kg) *	Total CO_2 emissions (%) **
Residential	26	416000	41.6	21	336000	41.0
Villa	54	135000	13.5	48	120000	14.6
Commercial	35	35000	3.5	31	31000	3.8
School	24	216000	21.6	18	162000	19.8
Center	20	50000	5.0	16	40000	4.9
Health center	28	56000	5.6	24	48000	5.9
Infrastructure	5	92500	9.2	5	83250	10.1
Sum		1000500	100.0		820250	100.0

* Total CO_2 emissions (kg) = CO_2 emissions (kg/m^2) × Total area (m^2)
** Total CO_2 emissions (%) = Total CO_2 emissions (kg) / Sum × 100

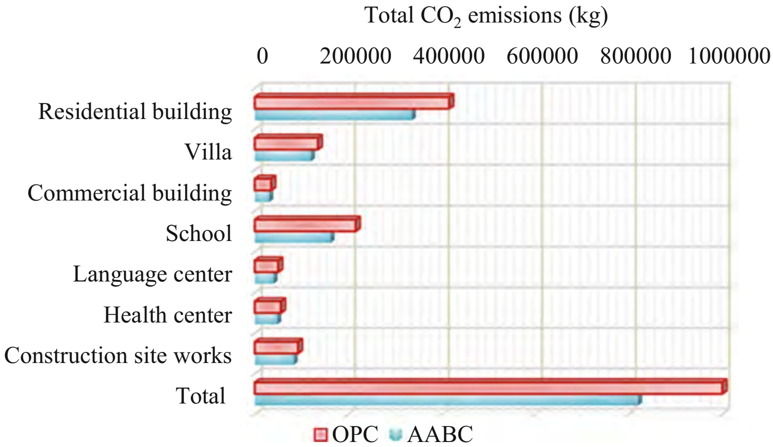

Fig. 4. CO_2 emissions values for OPC and AABC concretes for various building types.

5 Conclusion

The LCA is a useful tool capable of considering and combining a wide range of environmental aspects for the purpose of providing a complete picture of system sustainability. The analysis provided in this study addressed key environmental aspects that are important for choosing between two or more alternatives as well as optimizing the system. The findings of the LCA may assist and guide stakeholders and decision-makers toward environmentally friendly and sustainable techniques for their application in the development of the built environment. A comparison between the OPC and AABC revealed that the AABC results in more favorable sustainability outcomes measured in terms of CO_2 emissions. It can be observed that the CO_2 emissions using the AABC are significantly lower than the OPC, which attests that the use of the AABC is desirable in greenhouse construction. The total CO_2 emissions resulting from residential buildings are the highest, since the majority of buildings in a typical built environment are residential buildings. This could be a direct motivation for imposing sustainability-proactive regulations on residential buildings to enhance the sustainability of the built environment.

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Possible Utilization of Used Precast Building Elements Through Consideration of Concrete Carbonation Degree

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Abstract. Significant changes in the strategic goals of the construction sector at the global level have been visible in recent years. By implementing the fundamental principles of sustainable development and circular economy, the modern construction industry tries to contribute to a healthier environment by reducing CO2 emissions, minimizing waste landfills, and preserving non-renewable natural resources. The possibilities of reusing prefabricated concrete elements of existing buildings instead of their traditional recycling on a material level or disposing of them in landfills are analyzed in this paper. Special attention in the research was placed on the carbonation of prefabricated reinforced concrete elements of buildings, as it is one of the most frequent processes that accelerate the deterioration of RC structures. Long-term carbonation processes inevitably result in reinforcement corrosion and accompanying damage to the concrete cover, therefore some constrains for the further use of prefabricated RC building elements must be precisely defined. In this study, the potential use of prefab RC building elements was determined by calculating the depth of carbonation while taking into account the age of buildings and environmental conditions (relative air humidity, position of prefab element). Depending on the thickness of the carbonized concrete and the type and intensity of damage to the reinforcement and concrete, various variants for further use of the dismantled prefabricated RC building elements were proposed (reuse without restrictions, use in the interior of new buildings, use in less demanding facilities, reuse after application of a protective coating, replacement of the protective cover and reuse etc.).

Keywords: Concrete · Buildings · Service Life · Carbonation · Reuse · Circular Economy

1 Introduction

Concrete is the most consumed material in the world, with almost 30 gigatons of annual demand. In Europe, concrete waste alone contributes about 30% of the total mass of solid waste [5]. With an ever-growing demand, concrete production today accounts for a high share of air pollutants [7], and both the extraction of its raw materials and the landfilling of its waste threaten landscapes, biodiversity and ecosystems.

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There are several well-known strategies to reduce the Detrimental Environmental Impact (DEI) of the concrete industry, but more stringent application of these strategies and the development of new ones are needed as the direct CO_2 intensity of cement production globally increased by 1.8% per year between 2015 and 2020 [5].

The utilization of Circular Economy (CE) strategies can contribute to further limitation of waste accumulation, prolong the use of concrete, and introduce material recovery loops (Fig. 1). CE strategies should be implemented as follows:

- Extend the use of structures as long as possible without modification,
- Repair or rehabilitate them if needed,
- If building removal is unavoidable, deconstruct it and reuse its pieces in another project with minimal reprocessing,
- If components are not reusable, recycle them into the manufacture of a similar or different product by crushing and downcycling it as backfilling material in excavated areas and engineering works [11] or as replacement of natural aggregates in recycled aggregate concrete.

Extending the use and/or reuse are strategies to prioritize over recycling as they prolong the service life of existing products. Reusing reduces the demand for new ones and waste generation.

Strategic reuse of demounted concrete elements in new buildings may be one of the solutions that will support the transition to circular construction. To ensure wider application of concrete reuse, it is necessary to develop a methodology for the assessment of the structural condition of existing buildings, and the selection of elements suitable for reuse, including guidelines for their disassembly, storage, and installation. However, one of the main obstacles for wide application of concrete reuse is the uncertainty concerning the remaining service-life of concrete elements and evaluation of quality over the future service-life in a new building. [9].

All structures must maintain their key performance indicators like load-bearing capacity, fire resistance and etc. over time. The service life is obviously affected by the material/product quality which is decided at the design and production stage in relation to the intended use, target environment conditions and the expected level of performance required over the service life. The end of service life can be detected by the loss of performance that results from aging, frequent failures, and increased repair expenses [9].

Because of their durability, most concrete and masonry buildings are demolished due to functional obsolescence rather than deterioration. However, a concrete shell or structure can be repurposed if a building use or function changes or when a building interior is renovated. Concrete, as a structural material and as the building exterior skin, has the ability to withstand nature's normal deteriorating mechanisms as well as natural disasters [8].

Obsolete buildings are often structurally sound before their transformation or demolition, and the same is true for their load-bearing components once extracted. Indeed, buildings, especially in urban areas with high land pressure, are typically demolished for reasons unrelated to material grade and structural performance [5]. Their load-bearing systems are generally well protected from weathering during their service life, and their components, mostly concrete, could be used longer, that is, reused in new projects.

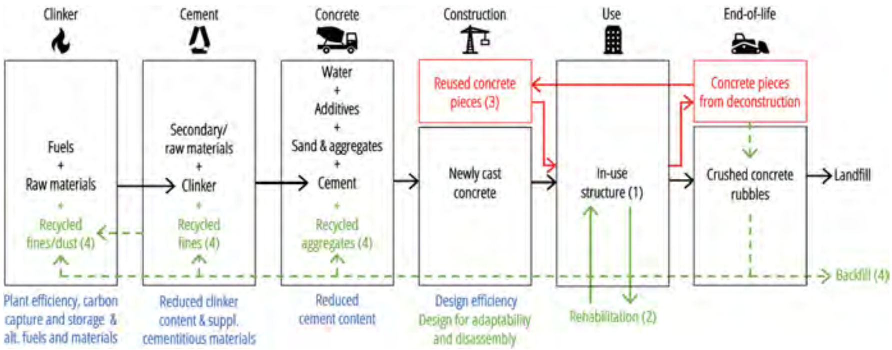

Fig. 1. Concrete value chain. In black, conventional concrete production and service cycle. In colors, trategies to lower the DEI of concrete: direct strategies in blue, circular strategies in green, circular reuse strategies in red. Numbers indicate the circular strategy priority to lower DEI. Adopted from [5].

Reuse is the second step in the waste pyramid after prolongation of the service-life due to preservation of the embodied value and, as such, it has minimal impact on the environment. To accelerate the transition from a linear to a circular economy, it is essential to ensure the quality of the concrete elements for reuse in terms of mechanical performance, physical properties, and longevity required by building standards. There are numerous obstacles to implementation of "reuse" strategies in the construction industry [6]. Some of them are:

– A lack of enthusiasm, as architects and engineers currently still prefer to build based on their ideas and do not want to be influenced by the design, structure, and size of previous reusable elements;
– Inability to use a standard template for planning reuse in each specific construction project. Individual measures and designs are required to ensure a construction process with reused concrete elements, and these extra activities increase the construction cost;
– Documenting the quality of building materials. The problem is occurs in documenting and tracking concrete quality in reused elements. The challenge is especially linked to the responsibility for the material quality.

On the base of carried out interviews [6] concluded the regulations and standards have a major impact on the development of increased reuse. That is, without more political incentives that force companies to build with reuse, improved development of reused concrete elements will be difficult to achieve. Therefore, current building norms and standards have to be updated to meet the challenges posed by circular economy [9].

In this paper the authors tried to predict possible utilization of used precast building elements through consideration of concrete carbonation degree.

2 Service Life

The design process of structures for the service life takes into consideration three main factors [9]:

- Limit values for performance indicators (in Eurocodes called limit states),
- Required period for the service life (in Eurocodes expressed as structure class),
- Reliability level of not passing over the limit values in the defined service life period (accounted for by safety factors applied on loads and material properties).

The durability of the structure is ensured by prescribing classes of expose (from XC to XA). They are necessary to define a depth of concrete cover and concrete important performances, from material with specific quality (cement, aggregate, additives, and admixtures), to cement content, water to cement ratio etc.

2.1 Service Life Calculation Tool for Reused Elements

The following approach to assessing the remaining service life of reused concrete elements will help real estate owners and structural engineers make decisions regarding their reuse. The approach started with:

- Analysis of existing documentation,
- Visual and full field surveys to check correspondence between the actual geometry of the structure with the available outline construction drawings or production of structural drawings that describe the geometry of the structure, allowing for identification of structural components and their dimensions, as well as the structural system to resist both vertical and lateral actions.
- Non-destructive testing; usually covers the evaluation of compressive strength (e.g. with Schmidt hammer), reinforcement scanning (e.g. with georadar), and determination of concrete cover (e.g. by reinforcement detector),
- Site sampling of built-in materials (taking concrete cores and reinforcement samples) for laboratory testing of their main properties (e.g. concrete compressive strength, carbonation depth, chloride ion content, steel tensile strength, etc.) and
- Field visual - condition inspection (detection of damages and defects, like cracks, spalling or surface decomposition of concrete, honeycombs, reinforcement corrosion etc.).

The estimation of residual service life (Lres) of concrete structures continues with following steps:

- Determining the condition of the materials (on the base of testing results) and defining the end of service life of each material in the structure, and
- Assessment of the damage degree according to results of visual inspection, and
- Making some type of time extrapolation from the present state to the state that characterizes the end of service life.

The calculation tool is used utilizing data from the condition assessment. The element was always given two lives: (I) Degradation of concrete cover (initiation based on the Fick’s 2nd law) and (II) Corrosion of steel (propagation based on corrosion rate in certain atmosphere). In the first life the diffusion coefficient was calculated based on status achieved from the laboratory tests and the age of the structure. The user is asked to define the target environment (e.g. exposed to chlorides or just to carbonation and relative humidity). Using the procedure presented in [9], the reference service life (Lref) could be calculated, as well as the residual service life, Lres.

Finally, all the collected results are evaluated, and recommendations on element classification for reuse are made.

3 Durability

The durability properties of concrete have an important role in assessing residual service life and defining the potential ways of reusing RC structural elements. Durability is defined as the ability of material to last a long time without significant deterioration. A durable material helps the environment by conserving resources and reducing wastes and the environmental impacts of repair and replacement. Concrete is considered as a building material with good durability properties. The durability of concrete may be defined as the capability of concrete to resist weathering action, chemical attack, and abrasion while maintaining its desired engineering properties [1]. Different concretes require different degrees of durability, depending on the exposure environment and properties desired. For example, concrete exposed to tidal seawater will have different requirements than an indoor concrete floor. Concrete, as a structural material and as the building exterior skin, has the ability to withstand nature's normal deteriorating mechanisms as well as natural disasters.

The main reason for the deterioration of reinforced concrete (RC) structures and the reduction of their durability is the corrosion of steel reinforcement. Reinforcement is protected by the surrounding concrete which is a highly alkaline environment with a pH value approximately 13 [2]. This ensures chemical protection of steel reinforcement with a thin oxide (passivation) layer. Two processes can cause reinforcement corrosion: concrete carbonation and chloride ion ingress in concrete. Carbonation-induced corrosion has been reported as a major durability problem in urban environment, considering a large number of buildings that are exposed to a CO_2-rich environment.

3.1 Concrete Carbonation

Carbonation is the process where CO_2 from the atmosphere penetrates through concrete pores and with pore solution forms weak carbonic acids (H_2CO_3). These acids react with portlantide ($Ca(OH)_2$) in the pore solution and are deposited as calcium carbonates ($CaCO_3$) which line the internal surfaces of the concrete pores. Described reaction leads to the decrease of the pH value in concrete. Depletion of hydroxyl ions (OH^{-1}) lowers the pore water pH from above 12.5 to below 9.0 where the passive layer becomes unstable, allowing general reinforcement corrosion to occur if sufficient oxygen and water are present in the vicinity of the rebar [2]. The carbonation depth in natural conditions directly influences the concrete cover depth required for the desired service life.

Evans [12] defined the reinforcement corrosion types as general corrosion, localized corrosion, and pitting corrosion. Also, the microcell and macrocell corrosion mechanisms may exist in RC structures. Microcell corrosion occurs when anodic and cathodic half-cell reactions take place at adjacent parts of the same metal. On the contrary, macro-cell corrosion takes place when the actively corroding rebar is coupled to another rebar, which is passive, either because of its different composition or because of different environment. Through a 3-year monitor program, Hansson et al. [12] concluded that microcell corrosion is the major mechanism of corrosion in RC.

A variety of interrelated factors influence the carbonation depth in concrete, such as: effective CO_2 diffusion coefficient, curing condition, age, cement type, presence of mineral admixtures, surface concentration of carbon dioxide, time of wetness, ambient temperature, relative humidity, etc. Environmental conditions, such as sheltered versus exposed and underground versus atmospheric, also have an important impact on concrete carbonation process.

The carbonation process occurs in almost all concrete structures but at different rates depending mainly on the humidity level. The most severe conditions accelerating carbonation occur in around 50–70% RH which in practice often means wetting and drying cycles (ex. buildings facades). However, the process happens also at lower pace in drier environments (e.g., in-house).

Concrete carbonation and carbonation-induced corrosion occur naturally in RC structures at a rather slow yet invasive rate. Carbonation-induced reinforcement corrosion usually affects a wider range of RC structures at a larger scale and belongs to general corrosion. There are lot examples of serious rebar carbonation induced corrosion even in hot and dry climate regions, such as North Africa.

Carbonation exposure class (XC) is the only one of the 5 classes of exposure according to EC 1992 (XC, XD, XS, XF and XA), which is always analyzed and defined for each element of RC structure, because carbonation is a spontaneous process that takes place in all environments (from dry to aquatic environments). The exposure carbonation classes, according to EN206, are shown in Table 1.

Table 1. Exposure classes related to carbonation (adapted from EN 206, 2013)

Class designation	Description of the environment	RH (%)	Informative examples
XC1	Dry or permanently wet	<40	Concrete inside buildings with low air humidity
XC2	Wet, rarely dry	>80	Concrete surfaces subject to long-term water contact
XC3	Moderate humidity	50–70	Concrete inside buildings with moderate or high air humidity
XC4	Cyclic wet and dry	-	Concrete surfaces subject to water contact

To determine the residual service life of concrete elements when their reuse is planned, the carbonation class must be redefined.

3.2 Cracks in Concrete

Cracks are characteristic for all brittle materials, especially for concrete. They occur when the internal stresses exceed tensile strength of material. They may appear regardless of the concrete age or state: before and after hardening, in unloaded concrete, or in concrete elements under the load According [10], 18 different causes induce cracking occurrence. They are classified into physical, chemical, thermal, and structural groups based on their origin. Cracks generally reduce the mechanical properties and endanger the durability of concrete. They reduce the shear capacity of the cross-section, allow the penetration of moisture, oxygen, carbon dioxide, and chloride into the concrete, and, over time, the corrosion of the reinforcement can be initiated. Due to their width limits, cracks are conditionally permitted in most reinforced concrete structures. The key issue in cracked concrete is obtaining the required durability since the steel reinforcement continues to transfer loads even after cracking. The maximum allowed crack width depends on the reinforcement type (normal reinforcement or prestressing) and the reinforcement grade. Since most prestressed constructions are designed to resist decompression (cracking), their limits are often tougher.

According to the requirements of Eurocode 2, the acceptable crack widths range from 0.4 to 0.3 mm for structures with an expected service life of 50 years. The maximum design cracks with (wmax) is 0.4 mm for exposure classes X0 and XC1, wmax = 0.3 mm for reinforced concrete in XC2, XC3 and XC4, and wmax = 0.2 mm for prestressed concrete regardless the classes of exposure. If the cracks are large enough, they accelerate the rate of carbonation [4]. However, the rate of carbonation is not only affected by the surface crack width, but also by its depth, interconnection with other cracks or voids, and the location of cracks with respect to reinforcement. In general, it is agreed that cracks finer than 0.05 mm do not affect the diffusion properties, due to self-healing process. The crack width has also to be included as a criterion for disassembled element quality classification.

4 Assessment of Concrete Carbonation Degree

The degree of carbonation can be easily evaluated through concrete and reinforcement damage analysis. The following damages are characteristic:

- Cracking and spalling of concrete,
- Reduction in rebar property (cross section area and bearing capacity), and
- Loss in interfacial bond strength.

They together may cause a significant reduction in the load-bearing capacity of structure elements individually or of the whole structure.

The authors of the paper propose three degrees of concrete carbonation based on the severity and type of damage:

I - Initiation period; the carbonation process has started, but it is sufficiently reliably estimated that it progresses slowly and that the carbonation front is $<<$ than the thickness of the concrete cover. The reinforcement still has satisfactory protection against the electrochemical corrosion of the steel in the alkaline environment surrounding it.

II - Propagation period; the carbonation process is in progress so that the carbonation front has reached close to the reinforcement ($d_{carb.} </\approx d_{cover}$) The reinforcement gradually loses its passive protection against corrosion. Cracking of concrete is possible.

III - Developed period; the carbonation process is fully developed and the carbonation front has passed behind the reinforcement bars. The reinforcement does not have the necessary corrosion protection and the electrochemical corrosion of the steel has already advanced. Possible visual manifestations are cracking and spalling of concrete, flaking and “enlargement” of rebar volume, and loss of interfacial bond strength.

5 Possible Utilization of Used Precast Building Elements Through Consideration of Concrete Carbonation Degree

The following five utilization scenarios for used precast building elements are given based on the degree of concrete carbonation:

Reuse - use of existing concrete structure elements in origin state.

Upgraded reuse - adding new layers such as thermal insulation, fire protective cover, applying protective materials to prolong durability, etc.

Repair and reuse - repair of concrete and reinforcement damages.

Recycling - production of aggregate for partial or total replacement of natural aggregates in concrete.

Downcycling - crushing and usage as backfilling material.

The possible utilization scenarios of used precast building elements regarding their concrete carbonation degree, are suggested in Table 2.

Table 2. Utilization scenarios versus concrete carbonation degree

Concrete carbonation degree	Reuse	Upgraded reuse	Repair and reuse	Recycling	Downcycling
I - Initiation period	✓	✓	-	-	-
II - Propagation period	-	✓	✓	-	-
III - Developed period	-	-	-	✓	✓

6 Conclusion

In this paper the authors tried to predict possible utilization of used precast building elements through consideration of concrete carbonation degree in line with CE strategies in construction industry.

Three degrees of concrete carbonation based on the severity and type of damage are proposed: I - Initiation period, II - Propagation period and III - Developed period.

Five utilization scenarios for used precast building elements are analyzed based on proposed degrees of concrete carbonation.

If reuse scenarios are chosen, the residual service life of concrete elements should be determined, in which the carbonation class is among the major factors that endangered concrete durability.

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Geo- and Bio-Based Materials as Circular Solutions Towards a Regenerative Built Environment

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Abstract. Global environmental awareness pushes the building sector to achieve carbon neutrality and find low embodied impact solutions. The European Union has set a 2050 goal and is regulating the whole carbon life cycle (embodied and operational) as part of the Energy Performance of Buildings Directive (EPBD). In this scope, low-tech geo-bio-based materials can have an important role in reducing the embodied environmental impacts and carbon in buildings. Due to their low processing production, these materials fit in a circular approach since they can be easily recycled or returned to the natural environment at a minimal environmental cost. However, the lack of quantitative data on the life cycle environmental performance of some non-conventional techniques can hinder their use since professionals cannot compare the benefits of such versus conventional practice and comply with future EPBD requirements. This paper aims to contribute to the topic by presenting results on the life cycle environmental performance of earthen materials and bio-based insulation products versus conventional solutions based on data from Environmental Product Declarations or studies following the EN15804 standard. The results show that earthen materials can reduce the potential environmental impacts by about 50% versus conventional mansory walls. At the same time, bio-based insulation solutions offer the advantage of lowering operational carbon emissions and stocking carbon (e.g. straw has a Global Warming Potential performance about three times better than Expanded Polystyrene). The benefits of using earthen and bio-based materials are also discussed for the different building life-cycle stages, focusing on the possibility of reusing/recycling these materials in a closed-loop approach.

Keywords: Earthen materials · Bio-based materials · Low-carbon materials · Circular materials · Life cycle assessment

1 Introduction

Regarding the current climate change scenario, the struggle to limit global warming to a 1,5 ºC rise in temperature comes up against the high level of CO_2 emissions over the last decades. According to the International Panel on Climate Change (IPCC), all sectors have options to at least halve emissions by 2030 [1]. For the built environment-related sectors

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(cities, buildings, and industry), there are substantial emissions reduction opportunities through measures such as lower energy consumption, carbon storage in natural solutions, efficient use of materials, reusing and recycling products and minimising waste [1].

The built environment is a key sector to intervene since it is responsible for almost 40% of CO_2 emissions [2]. In 2022, about 9% of those emissions were related to building materials [3]. Among building materials, concrete and steel are the most important contributors to the embodied carbon of all building types, representing more than 60% of it [4]. The OECD report on global resources stated that the use of materials will rise from 79Gt in 2011 to 167Gt in 2060 [5]. At the same time, materials management emissions related will grow from 28Gt to 50Gt of CO_2 eq. by 2060 [5].

Adopting circular solutions could reverse the trend and avoid exceeding several planetary boundaries. According to the most recent Circularity Gap Report, such adoption could lead to a significant 145% decrease in climate change and an even more substantial 190% reduction in land system change [6]. However, according to this report, nowadays, just 7,2% of the total material comes from circular inputs, known as secondary materials. The report explains that it is not only due to our incapacity to recycle but also because we are building more. The circularity metrics have fallen since the first report (2018), which stated 9,1%. Material choice becomes a key point for a circular economy and a regenerative built environment. The growing environmental awareness will increase the demand for more sustainable solutions, therefore forcing the construction industry to follow the path towards a circular economy, sustainable resource management and environmental protection [7, 8].

Concerning the European context, strategies such as the European Green Deal address decarbonisation, aiming to reduce greenhouse gas emissions by 55% by 2030 and making Europe the first climate-neutral continent by 2050 [9]. To achieve this goal, the Energy Performance Building Directive (EPBD) recast 2022 [10] demands for new buildings from 2030 onwards, the calculation of the life cycle Global Warming Potential (GWP), as well as predicts at least double renovation rates from 2020 to 2030. Northern European countries, such as Denmark and Sweden, have even more ambitious plans to deal with the environmental impact of buildings. Denmark targets to reduce new housing emissions from 482 to 20 $kgCO_2$ eq/m^2, while life cycle emissions would be reduced from 9,6 in 2020 to 0,4 $kgCO_2$ eq/m^2 in 2029 on a most optimist scenario, on a 50—year reference period [11]. The Danish Reduction roadmap also intends to reduce the number of new buildings by limiting the permitted square meters per year and reducing the square meters per person [11]. In the case of Sweden, it aims to bring greenhouse gases emissions to zero by 2045, becoming the first fossil-free country in the world [12]. Among the Swedish actions is a significant reduction in emissions from heating, which includes combined heat and power production plants and district heating systems for buildings [12].

As buildings become more energy-efficient, attention turns to the increasing relevance of embodied emissions in materials [4]. In this framework, geo and bio-sourced materials have the most negligible impact as they tend to be locally available for construction. These kinds of materials have been present in the construction community for a long time, as vernacular construction is based on them. In the scope of sustainability, vernacular architecture holds significant importance, as this type of construction carries the notion of being built to meet the needs in which its strategies and materials are the basis of sustainable construction. Research conducted globally has demonstrated that its features play a crucial role in ensuring comfortable living environments, lowering environmental impact, reducing energy consumption and consequently mitigating CO2 emissions [13–18]. Contemporary construction needs to adapt vernacular materials to current projects.

In order to reduce energy and materials demand, it is essential to prioritise energy-efficient systems through passive strategies and incorporate circular materials whenever possible, as emphasised in the Circularity Gap Report 2023 [6]. Natural materials used in vernacular architecture, such as earth and fibres, have considerably lower embodied energy and carbon dioxide emissions than conventional materials and can reduce environmental impacts associated with buildings [8, 18, 19].

The transition from a linear to a circular production model, characterised by an ongoing cycle of recycling, production, use, and recycling, is imperative. The transition from a linear to a circular production model, characterised by an endless cycle of recycling, production/transformation, use, and recycling, is imperative. Therefore, it is important to predict the use of low-carbon impact materials, such as geo and bio-based materials with a high recyclability rate. Materials can transform buildings into carbon sinks and, at the same time, be guaranteed to be reused or recycled. Low-processed materials do not require significant effort to be reused since they can be disassembled and transformed for reapplication. The recycling processes must guarantee the original level of quality of materials rather than downcycle them [20].

However, there is a lack of quantitative data on the benefits regarding environmental performance and recyclability rate of geo- and bio-based materials, which hinders professionals from comparing and specifying these products. In this context, this work discusses their environmental performance and contribution towards a construction based on natural building materials.

2 Geo- and Bio-Based Construction Materials

Geo-based materials are the ones from mineral-origin resources, such as raw earth and dry stone. On the other hand, bio-based materials are partially or entirely from biomass, such as wood, hemp, straw, cork, sheep's wool, etc. Both, when minimally processed, tend to have a low environmental impact, and when reused or in the form of by-products or co-products, such as recycled textiles or wooden boards, they enter into a circular economy logic.

Humanity has used geo- and bio-based construction materials for as long as shelter was needed, relying on renewable resources or abundant reserves, leading to easy recyclability and economically efficient products [20]. However, many of these natural materials are hardly associated with progress and even rejected for connotation to subdevelopment. Regardless, in some contexts, using these materials is related to a luxury lifestyle, and their value is overpriced.

Pricing of building materials often ignores the fair labour and environmental costs of conventional materials, potentially distorting their true affordability. Regenerative materials may appear more expensive initially due to low demand and skilled labour.

However, recognising their true costs, including environmental factors, could position them as more cost-effective in the long term. Berge [20] argues that current prices, influenced by green taxes, obscure true environmental expenses. A shift towards a more realistic assessment of material costs is crucial to promoting sustainability and equity in the construction industry.

Developing and improving geo and bio-based materials is an asset for new buildings but mainly for the renovation market, reducing the embodied environmental impacts of interventions. Additionally, as these materials are natural, low processed and do not contain chemical content, they also contribute to a better indoor air quality than in conventional buildings. In some cases, as earth and natural fibres, their vapour-free and hygroscopic inertia properties also allow them to self-regulate moisture passively.

2.1 Earthen Construction

Earthen construction has deep historical roots and has been used for centuries, with many examples found across diverse cultures globally. Nowadays, it is gaining renewed attention due to its inherent ecological features and being used and adapted to contemporary buildings and needs.

There are many earthen-building techniques, developed and adapted to specific geographic contexts. Some of the most common earthen construction techniques include: i) adobe bricks, made from a mixture of earth, water, and sometimes straw, moulded and sun-dried; ii) rammed earth, entails compressing layers of earth within a formwork to build massive solid walls; iii) cob consists of blending clay, sand, and straw, and it is often used to build robust walls and sculptural structures; iv) compressed earth blocks can be considered a modern and improved version of adobe bricks, created by compacting a mixture of earth, water and sometimes stabilising agents, and has become one of the most versatile techniques for contemporary use. This technique is known for its durability and thermal mass properties, making it suitable for sustainable and energy-efficient construction.

These techniques are known for their durability and thermal mass properties, particularly rammed earth. Their high thermal and hygroscopic inertia helps to regulate indoor temperature and relative humidity, reducing the dependence on active heating or cooling systems. This not only enhances energy efficiency but also creates a comfortable living environment. Ongoing research and technological innovations aim to enhance the durability and stability of earthen structures [21]. These actions promote sustainable building practices, such as the circularity of the process. The circularity inherent in earthen construction, coupled with its deep historical heritage, positions it as a guiding force for future sustainable and innovative building solutions.

2.2 Bio-Based Insulation Materials

Bio-based insulation materials are usually sourced from plants/trees, including hemp, straw, cork, or wood. Additionally, they can be sourced from animals, such as sheep wool insulation, or from recycled materials like textiles or paper. Moreover, experimental natural insulation materials, such as mycelium-based ones, are gaining prominence in research [22].

As climate change increases extreme temperatures frequency, building's indoor comfort by passive means becomes a challenge. Despite insulation appearing to offer a proper solution for reducing energy demand for heating and cooling, most conventional insulation materials have complex industrial processes and pose significant harm to the environment, including high global warming potential. In this scenario, bio-based materials have the highest potential of lowering embodied carbon emissions in buildings due to their ability to stock carbon and contribute to mitigating climate change [23].

Nevertheless, the performance of these materials should not be evaluated based on a single factor but on the combination of various factors such as energy performance (thermal conductivity), environmental impact, carbon stocking and potential for end-of-life valorisation. Additionally, beyond energy-efficiency performance, when compared to conventional materials, bio-based materials offer advantages such as renewability, biodegradability, and a lower carbon footprint.

3 Environmental Performance of Natural Materials

Life Cycle Assessment (LCA) plays an important role in understanding and improving the environmental performance of a building through material choice. It is essential to assess their entire life cycle, from raw material extraction to end-of-life disposal or recycling. LCA provides a systematic and comprehensive framework for evaluating the environmental impacts associated with each stage of a material's life.

LCA methods are essential for manufacturers to identify areas for improvement within the life cycle of a material. This approach can contribute to minimise adverse environmental effects, improve resource efficiency, and promoting the adoption of more sustainable alternatives.

This work focuses on presenting the life cycle analysis results during the product stage (modules from A1 to A3), except for rammed earth, which includes the construction stage (A4-A5). Additionally, the potential benefits beyond the system boundary are also discussed.

Regarding earthen construction, many research studies emphasise the potential of earthen materials to reduce the environmental impact of buildings. However, the use of stabilisers in earthen solutions may differ in performance. Cement-stabilised rammed earth studies show that total embodied energy rises proportionally with cement content [24, 25]. For both earth blocks and rammed earth, the addition of lime, even in small amounts, emerged as a significant contributor to environmental impacts and embodied energy [18]. Thus, Arrigoni et al. [25] affirmed that creating durable mixes without stabilisers is possible. The study carried out by Fernandes et al. [18] also confirmed that adding hydraulic lime contributes to more than 60% of the value of all impact categories in module A3 (Manufacturing).

When assessing the global warming potential and embodied energy of conventional and earth-based solutions, noticeable reductions in values can be observed (see Fig. 1). Compressed earth blocks exhibit less than half the global warming potential of both ceramic and concrete blocks, a trend similarly observed in the case of rammed earth walls compared to alternative conventional solutions [26]. In terms of embodied energy, a similar trend is evident. Ceramic and concrete blocks possess 2.5 and 1.5

times more embodied energy than compressed earth blocks, respectively. Lightweight concrete blocks exhibit twice as much embodied energy, whereas ceramic blocks have approximately 0.45 times more embodied energy than rammed earth.

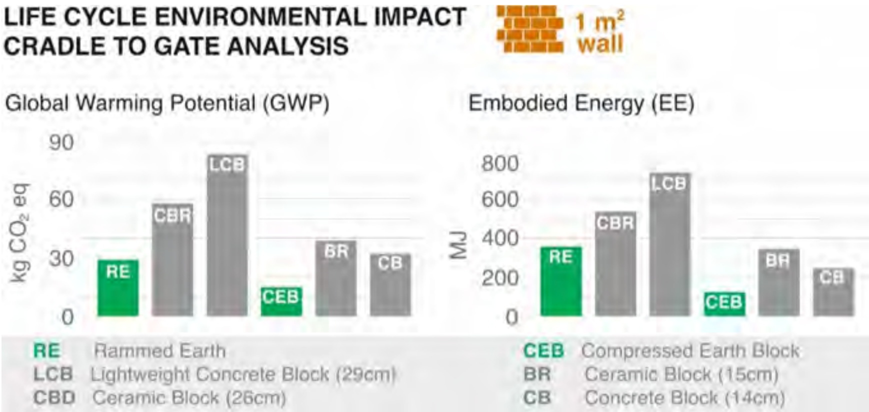

Fig. 1. Life cycle environmental impact comparison between earthen buildings and conventional solutions. Adapted from [26].

Regarding the life cycle analysis of bio-based insulation materials, the most significant advantage lies in their ability to store carbon during growth. In this sense, fast-growing plant-based materials, such as reed and straw, have proven to be particularly advantageous. The carbon sequestration during growth contributes to a reduction of overall carbon emissions, and along with their potential for recycling at the end of their life cycle, they are excellent choices for environmentally responsible insulation solutions.

A significant concern may be related to the thermal performance of bio-based insulation, yet only a greater thickness can match the performance of conventional materials while ensuring a considerably lower impact. The figure below (see Fig. 2) compares the thickness and emissions of known insulation products with the same thermal performance. While bio-based products require the same thickness or more than conventional products, their emissions are considerably lower or even "negative", i.e. stocking carbon.

Despite XPS foam and mineral wool requiring the same thickness to provide a thermal resistance of 5 (m^2K)/W, the global warming potential of XPS is more than ten times higher than that of mineral wool. While straw bale insulation is the thickest among the analysed materials, its rapid growth characteristic contributes significantly to a highly negative environmental impact and is about three times better than EPS foam board.

Among other advantages, it can be highlighted the renewable nature of bio-based materials, the low processing needed, which leads to energy efficiency in production, and biodegradability contribute to the end-of-life scenarios and circularity of the construction processes (Fig. 3).

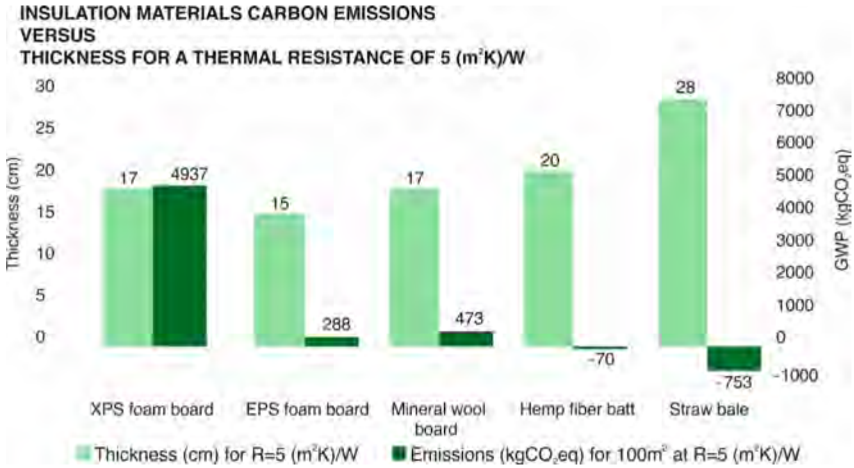

Fig. 2. Comparison between insulation material thickness and carbon dioxide emissions for a 5 $(m^2K)/W$ thermal resistance, considering product stage (A1-A3). Adapted from [23, 27].

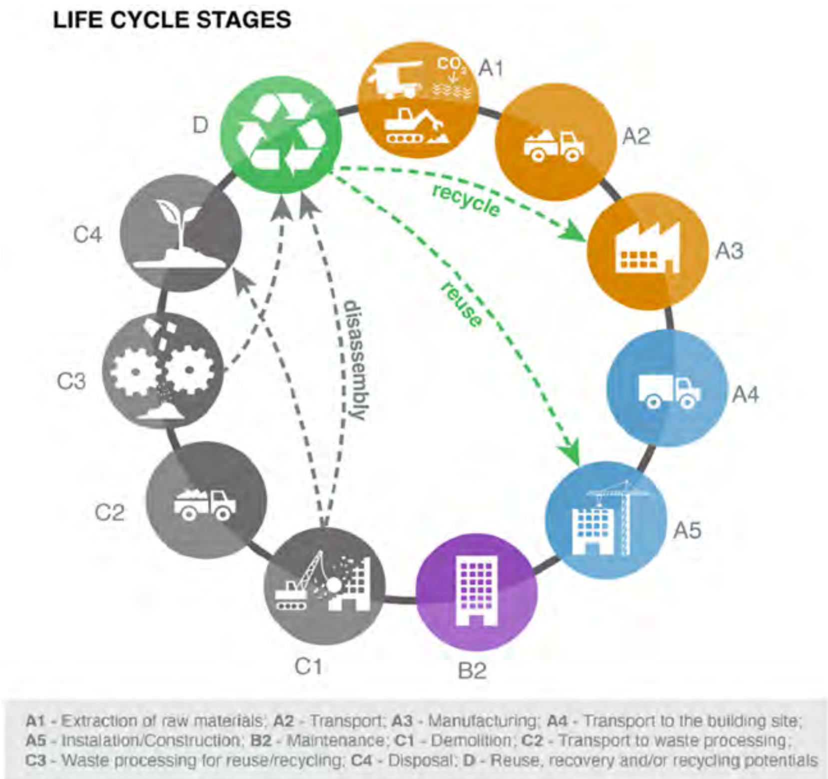

Fig. 3. Life cycle stages framework for building materials [18, 28].

It must be highlighted that geo- and bio-based materials can be easily recycled/reused into a new cycle, in some conditions with the same function as the previous. If not, disposing of the earth to the environment at a minimal environmental cost is possible since no harmful products were incorporated. As for other organic materials, such as plant-based, they can maintain their stocked carbon when in good condition and reused in construction or can serve as nutrients for further plant growth. Emphasising the proper disposal of these materials is crucial, as burning or depositing them in landfills releases the carbon accumulated throughout their life cycle.

4 Conclusions

Exploring geo- and bio-based materials in the context of a circular economy presents a transformative journey towards achieving a regenerative built environment.

These materials offer multiple benefits, from reducing carbon footprints to harnessing renewable resources, presenting a transformative trajectory for the industry that aligns perfectly with circularity and resource efficiency principles. Geo-bio-based materials can have a relevant role in the implementation of a truly circular economy in the building sector since they can be easily recycled/reused into new cycles, in some cases with the same function as the previous without downgraded quality, and by minimising waste and optimising the use of resources. When this is not possible, disposing of the soil has minimal environmental cost once it has no harmful products incorporated (e.g. non-cement stabilised soil). As for bio-based materials, they maintain their stocked carbon during proper reuse in construction, or they can be disposed of and serve as nutrients for further plants or even used for energy valorisation.

However, natural materials come with a set of challenges that need to be addressed for widespread adoption. Material consistency, regulatory intricacies, and the need for standardised practices are critical hurdles that demand strategic solutions. By better understanding its characteristics and continually developing actions to promote the use of these materials, it is possible to lead to a more resilient and regenerative built environment.

Due to the advantages mentioned in this paper, geo- and bio-based building materials have the potential to reduce the embodied environmental impacts of buildings, contribute to a truly circular construction economy and create healthy living environments.

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Waste Generation Factors and Waste Minimisation in Construction

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Abstract. The consistent growth of the construction sector during the last decades has generated massive waste that severely impacts the environment. Globally, construction activities generate around 30% of the overall waste annually, and the numbers are expected to increase due to population growth projections and the need for infrastructure developments. As a matter of fact, the causes of waste can be grouped into seven categories namely, design-related, procurement-related, human-related, handling and storage, site conditions, management-related, and due to other external factors, such as the effect of weather and accidents. In addition, construction waste types are influenced by project type, size, and construction method. To mitigate the impacts of construction waste, a plethora of practices have been recommended, including innovations for procurement, design, and construction. The present study scrutinises potential opportunities for minimising construction waste and proposes future sustainability enhancement related to construction activities. A pivotal contribution of this study is the creation of a matrix that links the identified causes of construction waste with sustainability practices, offering a comprehensive insight for effectively reducing waste and enhancing the sustainability of construction activities.

Keywords: Construction Waste · Waste Minimisation · Sustainability · Construction

1 Introduction

Construction waste (CW) is considered as a significant challenge in the building sector. Skoyles [1] defined CW as material waste that arises due to construction activities. Other sources define construction waste as the produced debris or discarded materials that occur during various construction activities and phases [2, 3]. Either way, construction waste is a major contributor to waste generation, harming the planet and impacting society and the economy [4, 5]. Consequently, it is widely acknowledged that addressing construction waste is a top priority issue.

Statistically, more than 32% of municipal waste is generated by construction activities worldwide [6]. In the EU, around 35% of the total waste is a construction source [7]. Similarly, CW represents 30–40% of the total municipal solid waste in the US, UK, and Australia, making the construction sector a primary source of materials dumping

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and landfilling [8]. In other regions, such as Jordan and Malaysia, CW amounts to more than 30 million tons and 9 million tons of waste on an annual basis, respectively [5].

Due to population growth and the excessive demand for construction and building projects worldwide [9], CW is anticipated to increase dramatically [6], among other reasons, as discussed in Loizou et al. [10], waste creation is inevitable in infrastructure projects with the current technology and construction methods. However, it can be mitigated through efficient management strategies. For instance, repurposing construction waste could improve environmental preservation and economic opportunities.

Waste minimisation is vital for sustainability, and focusing on waste sources is a critical step to reduce the environmental impact [8]. Several researchers investigated minimisation strategies and recommended multiple actions across various project stages that could be quantified throughout lifecycle assessments. Hence, this study aims to scrutinise the multifaceted causes of construction waste, and proposed strategies to mitigate it in the design, procurement, and construction phases, as informed by the existing literature. Subsequently, the causes of waste are associated with potential sustainability measures that could significantly contribute to its mitigation. Figure 1 shows the research process followed in this study.

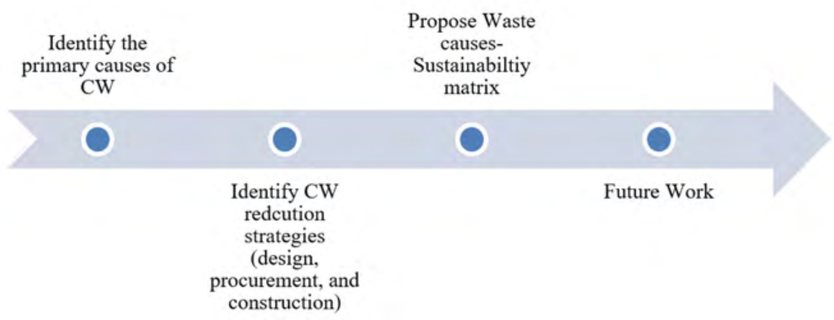

Fig. 1. Research process based on existing literature.

2 Construction Waste Generation

2.1 Causes of Construction Waste

The waste type and quantity in the construction sector are highly influenced by construction size, type, and technology used [11] while it is generated in different amounts during each project stage [12]. Researchers have found that CW multiplies due to design issues and errors, improper scheduling, reworks, lack of skilled labours, poor project management, materials storage and handling, and ill management of waste [5, 12–15]. Table 1 summarises the most common categorisations of construction waste.

It has been noted that the causes of construction waste generation are categorised differently by researchers. For instance, Al-Rifai and Amoudi [13] investigated the causes in

Table 1. Summary of the common construction waste factors in the literature.

Group	Construction Waste Causes	References
Design-related	Design complexity (W1)	[3, 15]
	Design documents errors (W2)	[3, 5, 13, 16]
	Design changes during construction (W3)	[3, 5, 15]
	Poor coordination & communication (W4)	[3, 5, 12–14]
Procurement-related	Ordering errors (W5)	[3, 13, 15]
	Buy low-quality materials (W6)	[3, 13, 15]
Human-related	Lack of experienced designers (W7)	[3, 13, 15]
	Lack of skilled workers (W8)	[3, 5, 13–15]
Handling and Storage	On-site transportation methods (W9)	[3, 13, 15]
	Inappropriate storage (W10)	[13–15]
Site Conditions	Leftover materials on site (W11)	[3, 13, 15]
	Poor site condition (W12)	[3, 5, 13, 15]
Management-related	Inaccurate planning and scheduling (W13)	[3, 12, 13, 15]
	Incapable site supervision (W14)	[3, 13, 14]
	Absence of waste management (W15)	[3, 5, 13, 15]
	Reworks (W16)	[3, 12, 13, 15]
External Factors	Weather (W17)	[3, 14, 15]
	Accidents in construction area (W18)	[3]
	Theft (W19)	[13, 14]

the Jordanian's building sector and classified waste factors in terms of their contribution to total amounts: high, medium, low, and very low. Obaid et al. [11] grouped construction waste into physical or non-physical, time and cost. Other researchers classified construction waste based on the construction stages [16]. For instance, they investigated waste minimisation in the design stage, procurement, and construction and classify waste accordingly [8]. Other studies categorised factors based on their origins; for example, Luangcharoenrat et al. [15] identified 28 factors contributing to construction waste and categorised them into four groups ranked from the most significant to the least significant: design and documentation, human-related, construction planning and methods, and materials and procurements. In addition, handling, site condition, and external factors are also identified as categories for construction wastes by Nagapan et al. [3].

CW cause factors are influenced by construction type and building techniques that also vary from region to region [15]. For example, a study by Al-Rifai and Amoudi [13] in Jordan found that construction waste is mainly driven by poor management and issues with the workforce. Instead, Nagapan et al. [17] identify poor site management and supervision as Malaysia's most significant construction waste factors. Hence, there is not yet a uniform categorisation criterion, which causes substantial delays in tracing the waste source and implementing the relevant strategies for waste reduction.

3 Construction Waste Minimisation

3.1 Design Stage

Engineering practitioners, academics, and scientists all emphasise the role of waste-efficient design, eco-design, and design for deconstruction to mitigate waste generation [18]. Ajayi et al. [19] place enhanced prefabrication techniques, pre-assembled components, and modular design as the core of waste reduction strategies in the design stage. Osmani [20] added to this by reporting on the current practices in the UK to minimise waste, which includes the standardisation of dimensions for steel and concrete profiles, prefabricated ancillary items, and design for disassembly. Olanrewaju and Ogunmakinde [21] further investigated strategies to reduce CW during the design stage and referred to Nigerian architects' most common strategies, including standard materials and products. Separate studies explore the effects of implementing BIM in construction projects and found that this facilitates sustainable construction and helps minimise waste by enabling design adaptability, which allows for more efficient planning and easier modifications, for example, Alasmari et al. [22]. We close this point by citing Laovisutthichai et al. [23], who state that the CW and construction cost could be reduced without compromising the design if we adopt the design for construction and waste minimisation (DfCWM) modern guidelines such as Wrap [24].

3.2 Procurement

Any improvement to design and management could not be separate from procurement. The main strategies suggested by the authors are on-time delivery, proper storage, purchasing products with little or no packaging, and over-ordering prevention [25]. Ajayi et al. [26] emphasised the importance of considering CW in procurement and identifying delivery management, supplier commitment to reduce waste, waste-efficient bill of quantity, and low waste purchase management as the main features in waste reduction during procurement. Furthermore, Nagapan et al. [27] identify ordering errors, shipping mistakes, and inaccurate quantity calculations as the causes of construction waste in the procurement stage. Thus, new reduction strategies could be developed to further integrate procurement into the production process.

3.3 Construction

Construction techniques can be improved through enhanced technologies, including using green materials, implementing relevant legislation, and implementing behavioural-based methods to increase worker efficiency [28, 29]. Additional on-site minimisation strategies are related to waste collection and reuse, although those are labelled as reactive strategies [30]. Waste source minimisation measures shall be considered in the construction phase under a rational structure, for example, through groups defined as field planning & management, and materials management [25, 26]. Hence, both the generated waste and its sources could be the focus to minimise sending materials to the landfill and maximise the benefits of the resource. Table 2 summarises waste minimisation practices in the current construction landscape.

Table 2. Summary of the common construction sustainability practices in the literature.

Construction Phase	Sustainability practice	References
Design	Waste-efficient design (D1)	[18, 26]
	Eco-design (D2)	[18]
	Design for deconstruction (D3)	[18, 20]
	Modular design (D4)	[19, 21]
	Prefabricated design (D5)	[19, 20]
	Standard design (D6)	[20, 21]
Procurement	On-time delivery (P1)	[25]
	Proper storage (P2)	[25]
	Purchasing products with little or no packaging (P3)	[25]
	Over-ordering prevention (P4)	[25, 26]
	Supplier commitment to reduce waste (P5)	[26]
Construction	On-site waste minimisation strategies (C1)	[30]
	Legislation (C2)	[28, 29]
	Behavioural approaches (C3)	[28, 29]
	Materials management (C4)	[25, 26]

4 Proposed Waste Causes- Sustainability Practices Matrix

The construction industry faces significant challenges in managing and reducing waste, raising concern for its environmental, economic, and societal implications. To address this, various sustainable practices have been proposed, targeting different waste causes in construction projects. Table 3 presents a linkage between common waste causes and sustainable practices, providing an insightful idea for enhancing sustainability in construction activities.

Table 3. Matrix linking sustainability practices to waste causes in construction projects.

Waste causes	Sustainability Strategies														
	D1	D2	D3	D4	D5	D6	P1	P2	P3	P4	P5	C1	C2	C3	C4
W1	√	√	√	√	√	√									
W2				√	√	√									
W3	√	√	√			√									
W4				√	√	√									
W5								√		√	√	√	√		√
W6								√			√				√
W7						√									
W8					√										
W9							√				√				√
W10							√	√	√	√	√				
W11	√	√		√	√	√						√	√	√	
W12											√	√	√	√	√
W13							√				√	√			√
W14											√	√	√	√	√
W15												√	√		√
W16				√	√	√					√				
W17							√	√		√					
W18											√				
W19										√	√			√	√

5 Conclusions and Future Work

The paper discusses the main issues related to construction waste (CW) and provides insight into the causes of construction waste. It goes on to address sustainability aspects and waste minimisation practices in construction projects.

The causes of waste have been previously investigated and categorised into defective planning, human errors, and design mistakes, including improper handling. These causes vary in their impacts based on the project's size, type, and technology used.

Strategies across the construction phases (design, procurement, and construction) are proposed from the literature to mitigate the risks associated with construction waste. Waste-efficient design, Design for Disassembly (DfD), and standard design practices minimise waste from the design phase. During procurement, key practices include avoiding over-ordering, reducing packaging, and ensuring supplier commitment. Meanwhile, in the construction phase, effective measures include on-site waste management and material management to mitigate construction waste.

The paper contributes to the field by identifying the leading causes of construction waste (CW) and underscores the importance of integrating sustainability practices into the main construction phases: design, procurement, and construction. Furthermore, this study contributes by constructing a matrix that links the identified causes of construction waste with sustainability practices, offering a comprehensive overview of effective ways to reduce construction waste. However, the study is limited to the existing literature, and empirical studies are needed to highlight the strategies' significance and impact on CW reduction.

Future studies should focus on quantifying the economic benefits of waste management, assessing the long-term social and environmental impacts, and validating the matrix through case studies to clearly outline the relationship between waste causation and sustainability practices, thereby ensuring a comprehensive understanding of the subject.

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Environmental Impact of Cold-Formed Z-shaped Steel Purlins

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Abstract. In an effort to mitigate climate change, the construction industry is moving toward a more responsible approach regarding production and design methods. The environmental impact of a structure must be reduced from the design phase by using reliable design approaches and choosing the production and construction processes that minimise as much as possible the carbon footprint. The purlins are components of the roof structure and their scope is to transfer the roof loads to the rafters. An efficient design of purlins is generally achieved by using cold-formed steel Z-shaped profiles. Z purlins span continuously over the rafters to reduce material use through a more favourable bending moment distribution. To ensure continuity of the bending moment along the length of the structure, the purlins form overlapped connections on the supports. The focus of this research paper is to assess through the Life Cycle Assessment methodology how the design influences the environmental impact of overlapped purlins. The paper assesses the impact of higher-grade steels versus more traditionally used steel grades. Furthermore, the adoption of steel manufactured using a high content of scrap steel and energy obtained from renewable sources facilitate the reduction of the carbon footprint of the element. Using advanced finite element models, previously validated against experimental results, the purlin systems were designed to support both gravity and pressure loads.

Keywords: Life Cycle Assessment · Embodied Carbon · Cold-formed · Purlins

1 Introduction

Cold-formed steel constructions have started to gain popularity due to their efficient use of materials and ease of fabrication. Cross-section shape flexibility represents a particularity for cold-formed steel profiles and makes them an economic alternative for secondary load bearing structures such as racking or high bay warehouses, but most

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recently also for small to medium rise buildings. The lightweight nature of these elements coupled with precise manufacturing tolerances allows for quick construction, typically without the need for heavy equipment. Cold-formed elements are typically manufactured from galvanised coils with thicknesses ranging from 0.5 mm to 3 mm and steel grades with strengths greater than 300 MPa. The profiles are commonly connected using bolts and screws, often avoiding welded elements, making them easily stackable for transportation and storage on-site.

An ever-growing concern regarding climate change is driving governmental bodies to promote and enforce sustainable practices for the built environment. The construction industry is recognised as one of the primary contributors to carbon emission. According to the Global Status Report for Buildings and Constructions [1], in 2021 the production of construction materials was estimated to contribute 37% to energy-related CO_2 emissions. The focus in recent decades has been to reduce the operational footprint of the building by improving energy efficiency. This focus was justified by the fact that operational carbon amounts to 28% while embodied carbon accounts for 11% according to a report by the World Green Building Council [2]. However, as the built environment evolves through continuous investment and innovation, it is expected that the embodied carbon footprint will become the main contributor to the overall footprint of the building. The need for decarbonisation is accelerated by the net-zero greenhouse gas emission target set for 2050 by the European Green Deal.

To evaluate the carbon emissions of buildings, a Life Cycle Assessment (LCA) can be used. LCA is a science-based and standardized methodology [3, 4] designed to quantify and report environmental impacts. The LCA serves to measure and guide the reduction of carbon emissions related to buildings and their components across their entire life cycles. This involves examining stages such as pre-use, during use, and at the End-Of-Life (EOL) of the building.

The purpose of this paper is to assess the embodied carbon footprint of a typical industrial hall roofing system. According to previous research [5], sigma cold-formed steel purlins have a lower global warming potential compared to prestressed prefabricated concrete or glulam timber. The focus of this research is to quantify the environmental impacts of a roof system consisting of cold-formed steel Z-shaped purlins and trapezoidal sheeting.

2 Methodology

Life Cycle Assessment (LCA) is a scientific and quantitative method designed to determine and evaluate environmentally relevant processes. Initially developed for evaluating products, it is now also applied to evaluate constructions.

The standard [3] outlines the steps that must be followed to complete a Life Cycle Assessment of a building: (1) Purpose and object of the assessment; (2) Boundaries of the analysis; (3) Life cycle inventory (LCI); (4) Calculation of the environmental indicators; (5) Interpretation of results; (6) Conclusions.

2.1 Purpose and Object of Assessment

The purpose of this LCA is to quantify the environmental performance of equivalent purlin roof configurations, composed of cold-formed steel elements and different steel grades. This comparative LCA can support the different players in the construction chain (e.g. engineers, architects etc.) in the decision-making process by providing comparisons of the global warming potential (GWP) expressed in $kgCO_2eq$ as defined in EN 15804 + A2 [6] for different design options and by indicating the potential for GWP reduction. The declared unit of the LCA to be used for the assessment and comparison between the different design variants is the square metre (m^2) of the purlin roof system.

2.2 Design Variants

The trapezoidal sheeting that represents the top outer layer of the industrial hall is supported by Z-shaped cold-formed purlins that span over the rafters. The continuity of the bending moment over the rafters was ensured in two options: continuous and overlapped purlin. Previous research [7] shows that overlapped purlins are superior from a mechanical behaviour point of view compared to sleeved connections. The use of high-grade steel has been shown to increase material efficiency by previous work of the authors [8], therefore three steel grades have been investigated S350GD + Z and S550GD + Z. ArcelorMittal's HyPer® high-strength steel grade S550GD + ZM satisfies additional requirements compared to the EN 10346 standard [9] by ensuring that ductility requirements are respected as defined in EN 1993-1-1, EN 1993-1-3 and EN 1993-1-12 [10–12]. Zinc-magnesium (ZM) coating is a brand product of ArcelorMittal called Magnelis®. In the framework of the EN 10346 standard [9], Magnelis® shall be classified as a ZM coating [13]. The coating is produced on a classic hot dip galvanising line in which the molten bath has a unique chemical composition that includes zinc, 3.5% aluminium and 3% magnesium.

The purlins were designed using a validated finite element model, as shown in Fig. 1, developed in the previous work of the authors [8]. The model consists of two equal spans of 4 m and 6 m.

To capture the sensitivity to buckling of the thin-walled members, the geometrically and materially nonlinear analysis with imperfections included (GMNIA) method of analysis was used.

The roofing components were designed according to the Eurocode framework. The loads considered for the ultimate and serviceability limit states were equal to 3.15 kN/m^2 respectively 2.2 kN/m^2. The material factor was assumed to be equal to 1.00 according to EN 1993-1-3 [11]. The individual vertical deformation of each component was limited to L/200 where L is the span. The sheeting was assumed to span continuously over three spans. The design variants used in the LCA are detailed in Table 1.

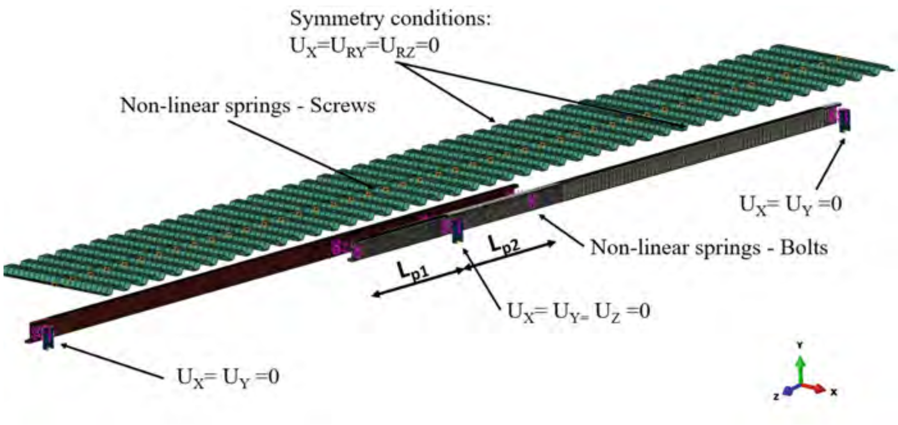

Fig. 1. Overlapped Z-purlin [8]

Table 1. Design variants parameters.

Design variant	Span	Cross-section	Connection at support	Steel grade	Steel sheeting	Purlin spacing [m]
Variant 1	4 m	Z150/47/41/17/1.2	Continuous	S350	35/207/0.55 S320	0.6
Variant 2	4 m	Z150/47/41/17/1.2	Overlapped $L_P =$ 450 mm	S350	35/207/0.55 S320	1.1
Variant 3	4 m	Z150/47/41/17/1.2	Overlapped $L_P =$ 450 mm	S550 HyPer®	35/207/0.55 S320	1.5
Variant 4	6 m	Z250/74/66/27/2.5	Continuous	S350	35/207/0.55 S320	0.9
Variant 5	6 m	Z250/74/66/27/2.5	Overlapped $L_P =$ 600 mm	S350	40/160/0.55 S320	1.6
Variant 6	6 m	Z250/74/66/27/2.5	Overlapped $L_P =$ 600 mm	S550 HyPer®	40/160/0.55 S320	2

Figures 2 and 3 present the weight of each of the different variants per area of the roof. The efficiency of using an overlapped connection over the rafters is demonstrated through the reduction in steel use by up to 40%.

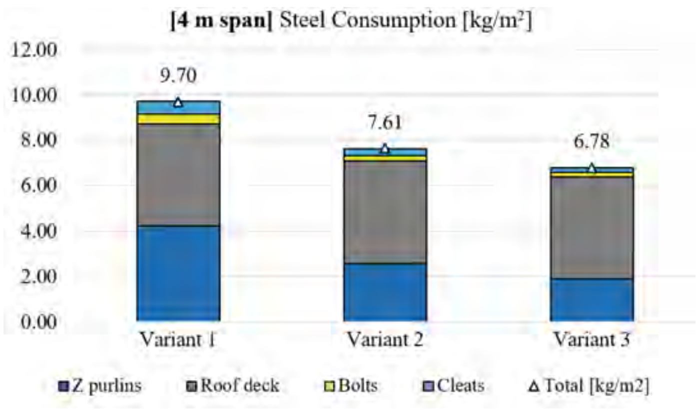

Fig. 2. Steel consumption for 4 m span variants.

Furthermore, increasing the yield strength from 350 N/mm^2 to 550 N/mm^2 reduced steel consumption by an additional 27%. The overlapped system designed using high-grade steels leads to an increase in purlin spacing by a factor of 2.5 for 4 m span beams and 2.2 for 6 m spans.

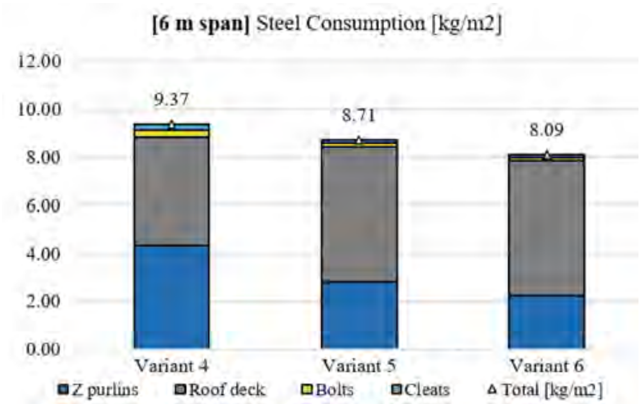

Fig. 3. Steel consumption for 6 m span variants.

2.3 Boundaries of the Analysis

The European Standard EN 15804+A2 [6] establishes a common life cycle model for materials and products applied to building and construction works. The life cycle model, shown in Fig. 4, includes modular definitions for the life cycle stages, allowing each stage to be compared in isolation with other stages.

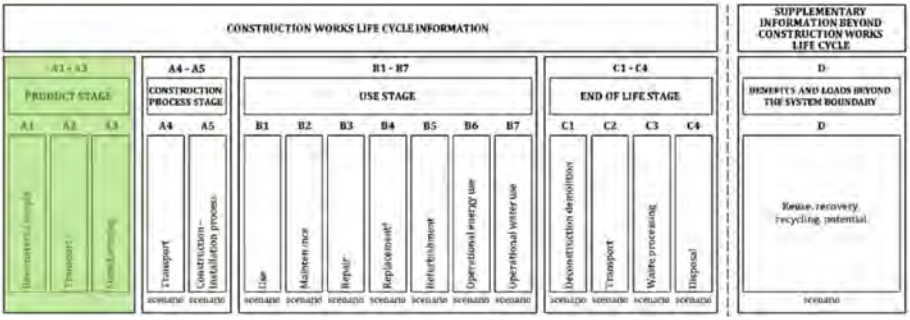

Fig. 4. The life-cycle model [6]

This current LCA specifically focusses on Product Stage A1–A3. Within this life cycle stage, emissions associated with resource extraction (A1), emissions related to resource transportation (A2), and emissions related to the manufacturing process, including the completion of finished products at the factory gate (A3), were considered.

2.4 Life-Cycle Inventory (LCI)

Environmental product declarations (EPDs) provide quantified information on the environmental impacts and aspects of products and services that are used in an LCA. The main EPDs and environmental data used in the current LCA are presented in Table 2 together with their impact at the Product Stage (A1–A3) in terms of their declared functional unit (FU).

ArcelorMittal's XCarb® Recycled and Renewably Produced (RRP) is applied to steels made in an electric arc furnace (EAF) using high levels of scrap (high recycled content) and 100% renewable electricity. Therefore, a great reduction in GWP related to metallic coated steel profiles can be achieved as presented in Table 2 when comparing, for example, the XCarb® Recycled and Renewable hot dip galvanised steel with Magnelis® coating versus standard steel produced in blast furnaces/blast oxygen furnaces (BF/BOF) as represented by hot-dip galvanised steel sheet (OEKOBAU.DAT).

Table 2. EPDs and Product Stage GWP emission factors.

EPD	Data Source	FU	GWP A1-A3 (kgCO2eq/FU)
XCarb® Recycled and Renewably produced hot dip galvanized steel with Magnelis® Coating (ArcelorMittal)	[14]	kg	0.797
Hot dip galvanized steel sheet (OEKOBAU.DAT)	[15]	kg	2.780
Deck profiles made of XCarb® recycled and renewably produced steel [4.5 kg/m^2] (ArcelorMittal Construction)	[16]	m^2	4.200
Deck profiles made of XCarb® recycled and renewably produced steel [5.6 kg/m^2] (ArcelorMittal Construction)	[16]	m^2	5.240
Trapezoidal Corrugated Steel Sheet for Construction Industry [4.5 kg/m^2] (Marcegaglia Buildtech)	[17]	m^2	13.250
Trapezoidal Corrugated Steel Sheet for Construction Industry [5.6 k/m^2] (Marcegaglia Buildtech)	[17]	m^2	16.470
Screw, Nuts HDG and accessories (Pretec)	[18]	kg	2.420

2.5 Calculation of the Environmental Indicator

The LCA analysis focusses on the GWP to describe the environmental impacts. The value of the GWP indicator is calculated for the product life cycle stages (A1–A3) based on a matrix calculation routine, as illustrated in Fig. 5.

For i = to the assessed life cycle stages [A1–A3].

The basic principle of this matrix calculation routine consisted of multiplying each product/material quantified in a module of the building life cycle with its respective value for any environmental indicator. Equation 1 exemplifies the resulting calculation routine for the quantification of the GWP of stage i:

$$GWP_i = a_{1,i} \times GWP_{a1,i} + a_{2,i} \times GWP_{a2,i} + a_{3,i} \times GWP_{a3,i} + \ldots + a_{N,i} \times GWP_{aN,I} \quad (1)$$

where:

GWP_i is the global warming potential quantified for module i of the purlin roof;

$a_{n,i}$ is the quantity of product/material used in the module i of the building (n = 1, 2, 3, …, N);

$GWP_{an,i}$ is the global warming potential of the product/material used in the module i of the building (n = 1, 2, 3, …, N).

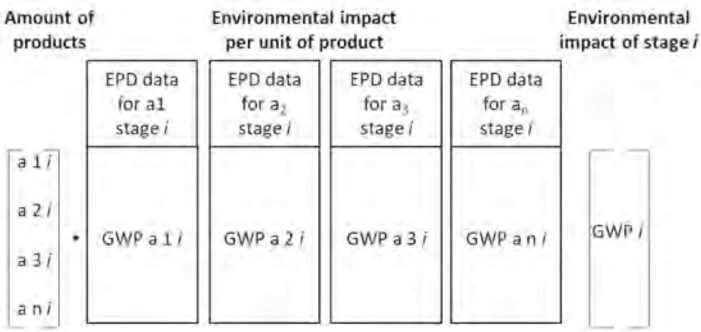

Fig. 5. The life-cycle model [6].

3 Results and Discussion

For the purlin design Variant 3 and Variant 6, two additional GWP assessments were made. The additional assessments referred as Variant 3 XCarb® and Variant 6 XCarb® highlight the benefits of the EAF process using recycled steel (scrap) and 100% renewable electricity during the steelmaking process. The results are presented in terms of the area of the purlin roof system. Figure 6 and Fig. 7 show the GWP result, highlighting the contribution of the different components to the GWP for two span configurations: 4 m and 6 m.

In general, regardless of the variant, the roof component with the most significant impact on the GWP is the cold-formed sheet decking, followed by the cold-formed Z profile. This outcome is in line with expectations, since both components account for the largest share of materials in the overall roof system. Specifically, cold-formed steel decking can contribute to overall GWP emissions by up to 71% (Variant 6). Similarly, cold-formed sigma purlins can influence the overall GWP by up to 45% (Variant 4).

For the 4 m span configuration the reduction of GWP between Variant 1, Variant 2 and Variant 3 is related to the reduction of the material consumption, since equivalent GWP emission factors were used to estimate the CO_2eq emissions of the different steel components. The reduction was achieved because using an overlapped purlin and increasing the yield strength of the profile. Overall, the GWP can be reduced by up to 29% when Variant 1 is compared with Variant 3. Similarly, for the 6m span configuration the reduction of GWP from Variant 4, Variant 5 and Variant 6 is also related to the optimisation of weight. Overall, the GWP can be reduced up to 13% when Variant 4 is compared with Variant 6.

In contrast to Variants 1 to 6, where the average European virgin steel production (BOF) is assumed for cold-formed steel elements, two additional variants, Variant 3 XCarb® and Variant 6 XCarb®, were considered. These variants integrate low-emission steel XCarb® for elements such as the roof deck, Z purlins, and cleats. These adjustments resulted in a substantial 77% reduction in the overall Global Warming Potential (GWP) when comparing Variant 1 and Variant 3, and a 72% reduction when comparing Variant 4 and Variant 6. These CO_2eq reductions are related not only to the weight optimisation of Variant 3 and Variant 6 compared to their counterparts, Variant 1 and Variant 4, but

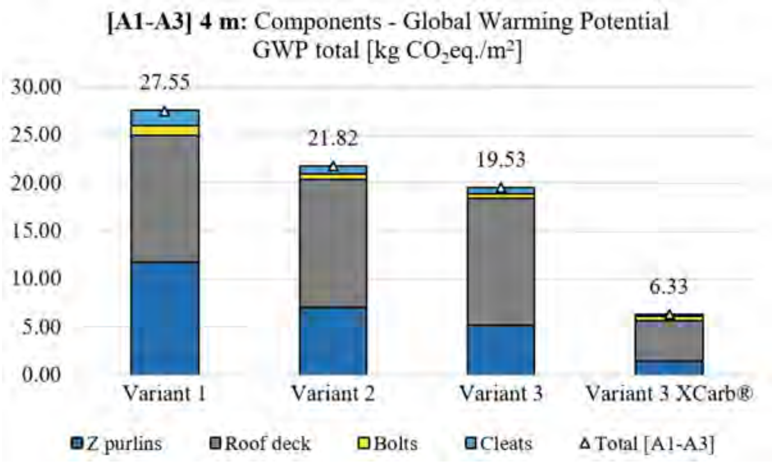

Fig. 6. GWP comparison in terms of components (4 m span).

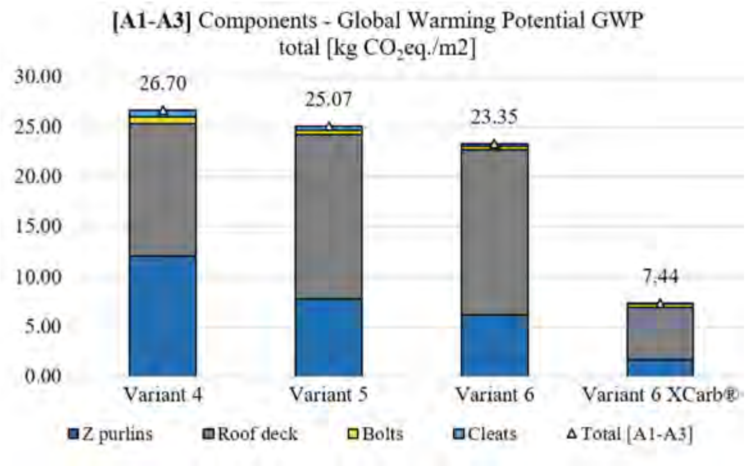

Fig. 7. GWP comparison in terms of components (6 m span).

also to the use of low-emission XCarb® steel. XCarb® is produced from an Electric Arc Furnace (EAF) with high recycled material content (steel scrap) and renewable electricity, leading to reductions in embodied carbon related to product stages A1–A3. The impact of XCarb® on the reduction of the GWP of global warming is evaluated by comparing Variants 3 and 6 with their respective XCarb® variants. XCarb® results in a GWP reduction of up to 68% when comparing Variant 6 to Variant 6 XCarb®.

4 Conclusions

The purpose of this LCA is to quantify the environmental performance of equivalent purlin roof configurations, composed of cold-formed steel elements and different steel grades and support the different construction chain players (e.g. engineers, architects etc.) in the decision-making process by providing comparisons of the global warming potential. In this research different purlin solutions were adopted. Two span configurations of 4 m and 6 m were investigated. A high-grade steel (S550) was used as an alternative to the more traditionally used S350. The connection over rafters was investigated in two options: continuous profile or overlapped purlin.

A Life Cycle Assessment from cradle-to-factory gate (product stages A1–A3) was conducted, and the Global Warming Potential for the six proposed variants was calculated. In the overall analysis, it was found that the roof deck and the Z-purlins account for the majority of CO_2eq emissions, reaching up to 71% for the roof deck in Variant 6 and up to 45% for the Z-purlin in Variant 4. These findings underscore the importance of optimising the design of purlins and roof decks in terms of weight by using high-strength steels, emphasising the need for using low-emission materials with high recycled content for these specific roof components.

In the 4 m span configuration, Variant 3 achieved a 29% reduction in Global Warming Potential (GWP) compared to Variant 1. This GWP reduction is associated with a decrease in material consumption through weight optimisation. This was facilitated by using a higher-grade steel together with an overlapped connection, instead of a continuous profile made of S350. Similarly, in the 6 m span configuration, Variant 6 yielded a 13% reduction in GWP compared to Variant 4. This reduction in GWP is similarly attributed to optimised material consumption. For the 4 m span configuration, Variant 3 reduced the GWP by 29% compared to Variant 1. This GWP reduction is related to a reduction in material consumption. Similarly, for the 6 m span configuration, Variant 6 reduced the GWP by 13% when compared to Variant 4.

Finally, two additional variants were examined, Variant 3 XCarb® and Variant 6 XCarb®, diverging from the standard use of average European virgin steel production (BOF) in Variants 1 to 6. These new variants, which incorporate low-emission steel, resulted in a 77% reduction in the overall Global Warming Potential when comparing Variant 1 and Variant 3 XCarb®, and a 72% reduction when comparing Variant 4 and Variant 6 XCarb®. These reductions are attributed not only to the weight optimisation of Variant 3 and Variant 6 compared to their counterparts, Variant 1 and Variant 4, but also to the use of XCarb® steel. XCarb® is produced from an Electric Arc Furnace with high recycled material content and renewable electricity, leading to substantial reductions in embodied carbon in the product stages A1–A3. The impact of XCarb® on the reduction in GWP was specifically assessed, revealing a potential 68% decrease when comparing Variant 6 to Variant 6 XCarb®.

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Environmental Impact Assessment of Buildings with Steel-Intensive Façade Systems – A Case Study

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Abstract. Global concerns about environmental sustainability have escalated in the last three decades, forcing industries to critically examine their practices and their contribution to the overall ecological footprint. The construction sector has become a significant contributor to environmental deterioration due to its extensive energy consumption, raw material extraction, and waste generation. One of the ways to reduce the environmental impact of the construction sector is to decrease the embodied carbon footprint of buildings using the three R approaches – reduce, reuse, recycle and by using renewable construction materials. The paper focusses on the evaluation of the behaviour of steel-intensive façade systems from an environmental impact perspective. The research presented in the paper shows a comparative Life-Cycle Assessment (LCA) of industrial buildings that have envelopes consisting of liner tray cladding systems and sandwich panel cladding systems. The results of this comparison show that when different envelope solutions are considered, the highest potential benefits (8–25% higher) occur for structures that have liner tray cladding systems and the highest loads (11–19% higher) appear for structures that have sandwich panel cladding systems. Moreover, the potential for repeated reuse in the case of claddings based on steel liner trays is superior to the potential for repeated reuse of sandwich panels, helping to reduce the environmental impact of the cladding system even after its second life cycle.

Keywords: LCA · liner tray · sandwich panel · embodied carbon footprint · comparative life-cycle assessment

1 Introduction

In an era defined by environmental concerns and resource scarcity, the construction industry faces the imperative to shift toward sustainable practices. At the forefront of this evolution are sustainable buildings, which strive to minimise their ecological footprint while maximising their functionality, comfort, and aesthetic appeal. Important in the realisation of sustainable buildings are innovative façade systems, particularly those that harness the strength and versatility of steel to create high-performance and environmentally conscious structures.

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According to the 2022 Global Buildings Climate Tracker and the United Nations Environment Programme, the construction sector and buildings are off track to achieve decarbonisation by 2050 [1, 2]. The report shows a negative trend in the decarbonisation of the building sector, achieving higher emissions since 2020. Greenhouse gas (GHG) emissions within the construction sector could be mitigated by reducing the embodied carbon footprint of the building accountable for extraction of raw materials, manufacturing of building materials, transportation of building materials, energy consumption related to the construction process, energy consumption related to the demolition/deconstruction process, transport of construction waste, construction waste process, and disposal. The reduction in construction materials emissions can be achieved through the use of renewable and recycled materials, the reuse of construction materials and components, the use of alternative materials with lower emissions and the adoption of sustainable manufacturing processes [3–5]. Reducing GHG emissions in the construction sector by addressing waste from construction materials may be achieved through recycling materials and reusing components at the end of buildings' lifespan, through design for deconstruction, upcycling materials for second lifespan, and using prefabricated construction elements [6–9].

A steel-intensive façade system is a building envelope that prominently features steel elements as a primary structural component and as an aesthetic component. Traditionally used in agricultural and industrial construction, in last decades steel-intensive façade systems have faced a growing demand in retail, commercial, and educational buildings [10]. Whether in the form of built-up wall steel insulated panel cladding systems, sandwich panel or liner-tray wall systems, or in the form of single skin façade panels and modular cassettes, steel-intensive façade systems have attracted increasing interest in the construction sector due to their strength, flexibility, and recyclability characteristics, emerging as a particularly inviting path to achieve sustainability goals.

In general, industrial buildings have a shorter lifespan (commonly 20–25 years, after which these buildings are usually replaced due to a change in demand) than other types of structures (50–100 years), leading to a higher ratio of embodied carbon to operational carbon compared to longer-lasting structures. This emphasises the importance of assessing the impact of materials and construction processes, as the proportion of embodied carbon emissions might be relatively higher. In the last decade, in the industrial hall and warehouse sector, approximately half of the structures were covered with sandwich panels and 50% with built-up systems with two skins [11].

The current results of research from studies that examine the life cycle of buildings have generated notable changes in the construction sector, guiding efforts to reduce emissions and improve energy efficiency [12, 13]. Thus, this study aims to contribute to existing research by a comprehensive analysis of the environmental impact of the most used industrial hall envelopes: sandwich panels and liner tray cladding systems as the latter have emerged as a promising technology that has the potential to transform the landscape of industrial construction.

2 Life Cycle Assessment of an Industrial Hall with Steel-Intensive Façade Systems

The purpose of the LCA presented in this paper is to assess the characteristics of single-storey steel-intensive systems using liner trays cladding systems and sandwich panels as envelope systems, through environmental impact analyses. The assessment includes single-storey steel structures made of completely new materials, as well as structures made of reused elements for the entire structure, for components (elements of the primary structure), or just for some individual members of the structure.

The case study is based on a LCA of a single-storey industrial building erected in Timisoara, Romania, and for the cases in which reclaimed steel elements were considered, it involved relocation from Germany to Romania.

Six scenarios for single-storey steel structures were selected for the environmental impact assessment (locations are important for transportation assessment):

- Baseline scenario (Case 0) in which the structure is designed as a new structure made with elements from new materials;
- The second scenario (Case 0+) considering a structure made of new elements with new materials, while the structure is designed for deconstruction;
- The third scenario (Case 1) referring to a relocated steel structure, considering the reuse of an existing steel structure that originated in Germany and was reassembled in Romania (after it was adjusted to local seismic requirements);
- In the fourth scenario (Case 2) it is weighted a steel structure made with reclaimed elements: existing profiles for beams and columns have been identified in a storage yard in Germany, which are deriving from other deconstructed buildings, and transported to Romania to be reused in a new industrial hall. All other components were made of new steel;
- The fifth scenario (Case 3) is similar to Case 2, considering reclaimed elements such as columns and beams, but also end plates for beams and columns. All other components represent new steel;
- The sixth scenario (Case 4) considers the reuse of an entire structure relocated from Germany. The percentage of steel reused in the superstructure is 100%.

The envelope considered for each case scenario involved two plots (Fig. 1): a) steel sandwich panels with mineral wool insulation (120 mm sandwich panels for the roof) and liner tray wall cladding with mineral wool insulation (100/600/0.75 liner trays with 60 mm mineral wool insulation for the walls) and b) solely sandwich panels with mineral wool insulation (120 mm sandwich panels for the roof and 80 mm sandwich panels for the walls).

For Cases 1 to 4, where the analysis involved reused materials, only the liner trays were considered for reuse - thermal insulation and outer steel sheet were considered in the investigation as new materials, as well as the sandwich panels used for the roof.

At the same time, for Cases 1 to 4 when the envelope was considered solely of sandwich panels, the existing envelope containing 80 mm steel sandwich panels with mineral wool insulation was reused, but to comply with the U-values existing in Case 0 and 0+, an additional layer of 60mm sandwich panels (new elements) was added to

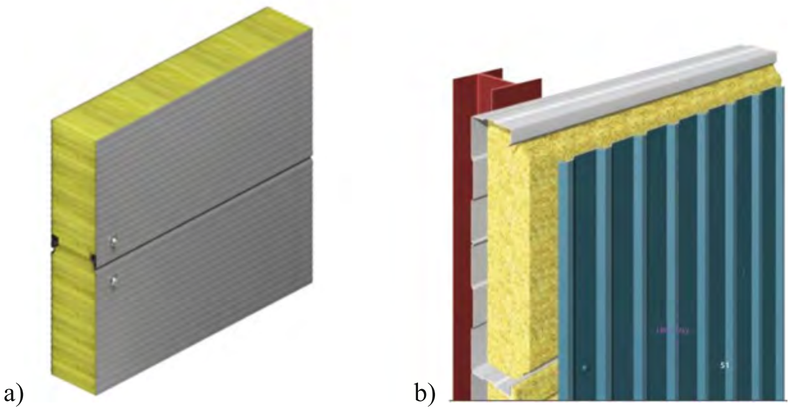

Fig. 1. Typical wall sandwich panel (a) and liner tray wall system (b) [14].

the entire envelope. The cross-section of the envelope consisting of sandwich panels is presented in Fig. 2.

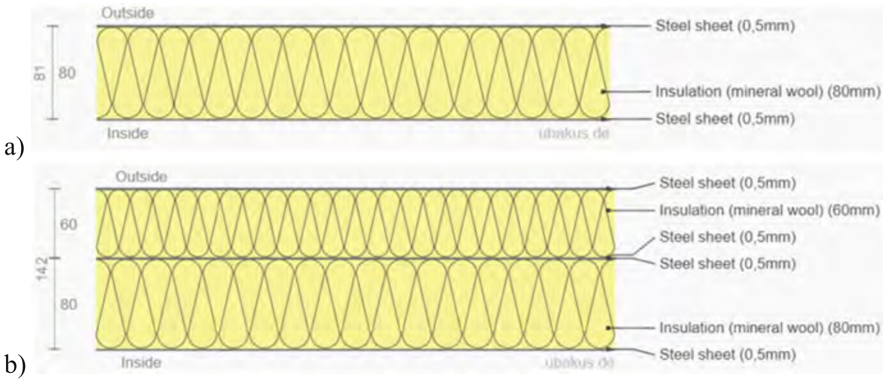

Fig. 2. Cross-section of envelope solution based on sandwich panels: a) envelope for Case 0 and Case 0+ b) envelope considered for cases 1 to 4 (image generated with [15]).

2.1 System Boundaries

The environmental assessment considered the following system boundaries for the described case studies:

- The main components of the building are the foundations and the ground floor slab (concrete and steel rebars), the steel load-bearing structure (hot-rolled and cold-formed steel elements), sandwich panels for the roof (steel sandwich panels with mineral wool insulation), liner trays cladding system or sandwich panels for the walls, triple glazed windows and sectional sliding gates;

- Other materials and components considered in addition to steel:
  - concrete foundations and concrete floor: 185 m^3;
  - triple-glazed windows: 22.5 m^2;
  - sectional sliding gates: 48 m^2;
- The steel rebars were counted as new material, with an input of 73% steel scrap in the manufacturing process and an end-of-life scenario with 95% recycling potential and 5% landfilling or material loss after sorting [16];
- The U-value considered in the assessment is in accordance with the Romanian standard in force [17]:
  - for the external walls - 0.56 $W/m^2 \cdot K$;
  - for roof elements - 0.34 $W/m^2 \cdot K$;
  - for ground floor slab - 0.76 $W/m^2 \cdot K$;
  - for windows and sectional sliding gates - 1.3 $W/m^2 \cdot K$;
- The heated floor area of the industrial hall is 525 m^2, for Cases 0, 0+, 2, 3, 4 having a total length of 30 m, with six identical frames in a bay of 5 m, a 17.5 m span and 6 m height at the eaves. In Case 1 the structure has 551.25 m^2 as the structure had to withstand higher loads than in Germany, thus the structure to be rebuilt in Romania has a length of 31.5 m, 7 bays of 4.5 m, and a width of 17.5 m in contrast to the structures in the other cases where they;
- The operational lifetime of the building is considered as 25 years.

2.2 Assessed Scenarios for the Environmental Impact

The LCA carried out presents a cradle-to-grave analysis, including loads and benefits beyond the system boundaries using the LCA software Sphera Solutions GmbH 2021 [18]. The declared functional unit in the analysis is one industrial hall including load-bearing structure, foundations, envelope, etc.

In the Production Stage (modules A_1–A_3) it was considered the manufacturing of the load bearing structure, foundations, floor slab, envelope, windows, and industrial sectional doors. LCA results are calculated for each case scenario considering a "new structure with new materials" and "reused elements" in which different amounts of reused steel were evaluated from the deconstructed industrial building halls. The product stage for reused elements includes blasting and coating (where required) [19].

In the Construction Stage (modules A_4–A_5) the assessment includes the transportation of all construction materials from the manufacturer to the building site (distances between 10 and 70 km), the transportation of equipment and the erection of the structure. For the reused steel structure (Case 1) and the reused elements (Cases 2, 3, and 4) the distance considered for the transport of the reused steel relocated from Germany was 1200 km. Building construction included the excavation of soil for the foundation and floor slab, the concreting and assembly of the steel structure and envelope using a 10t autocrane, forklifts, manlifts, wheel loader, bulldozer, excavator, concrete pump and packaging waste processing [18–20].

The life expectancy of the industrial hall in each case studied in this assessment is 25 years, with therefore maintenance (B2), repair (B3), replacement (B4) of elements, or refurbishment (B5) were not considered during the Use Stage (modules B_2-B_5). Evaluation of operational energy consumption was based on the energy demand for a distribution warehouse [21] and includes energy use for heating, cooling, lighting, IT, security, computers, and other systems. In the assessment, neither heat recovery nor mechanical cooling was considered. A similar heat transfer coefficient was targeted for all envelope systems (new or reused materials). The envelope systems have been compared using the dedicated online Ubakus software [15]. External and internal temperature values considered for the evaluation were −5 °C and 20 °C, respectively.

In the End-of-life Stage (modules C_1–C_4) the end-of-life scenario for each of the six cases studied involved an instance of "demolition and recycling" and another one of "deconstruction and reuse" (Module C1). It was assumed that the energy demand for the demolition of the steel load-bearing structure is 0.239 MJ/kg of steel product if the product is recycled and 0.432 MJ/kg of steel product if the product is reused [22]. For cold-formed steel elements, the impacts of deconstruction were modelled based on data from the literature on energy use in demolition, accounting for 0.085 kWh of diesel-powered machinery work per kg of steel deconstructed [23]. For concrete, the environmental impact included the use of diesel in the demolition process [24], while for reinforcement it included the consumption of diesel for the recovery of the reinforcement from crushed concrete [16]. The steel structure deconstruction process follows the reverse assembly process, to which additional effort is added to preserve the integrity of the deconstructed components for reuse [25, 26]. Where no other data were available, the supplementary effort was generated in the study as a 1.5 workload multiplier for the number of elements reused in the end-of-life.

The calculation model used for the assessment of Module D – Climate Change total [kg CO2eq] is based on an innovative calculation model [27], compatible with the methodology of the EN 15804 standard [28]. The calculation is based on the input and output of recycled and reused materials, the impact of virgin material production, and the impact of theoretical pure recycling.

3 Results of LCA

The environmental impact of the assessment was expressed using Total Climate Change as a pointer following the rules described in EN 15804 [28], EN 15978 [29] and ISO 14044 [30].

The LCA comparison (modules A-C) between cases with liner tray wall cladding and cases with sandwich panels envelope is presented in Fig. 3. The results of this comparison show that the Climate Change Total is higher in cases where structures are built with new materials and have liner tray wall cladding envelopes, regardless of the end-of-life scenario. The difference in additional 15–16 t of CO_2 e in these cases is mainly correlated with two stages of the life cycle: The highest amount of these additional emissions is recorded in the production stage (A_1–A_3) due to the high amount of steel and the environmental impact related to the steel production process present in the liner tray built-up wall system than in the sandwich panel envelope system; the rest of the amount of the additional emissions were recorded in the Construction Stage (A_4–A_5) due to the extra workload required by the installation of the liner tray built-up wall system, as double-shell systems in particular consist of many different individual parts.

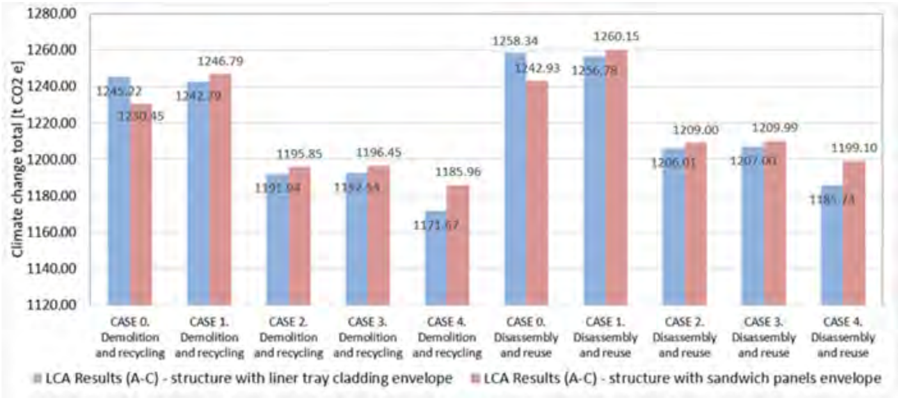

Fig. 3. LCA comparison (A-C) between structures with liner tray wall cladding envelope and structures with sandwich panels envelope.

However, Fig. 3 shows a clear trend of decreased rate of emissions in the reused case scenarios (Cases 1 to 4) for the structures with liner tray wall cladding envelope in both Demolition and Recycle scenario and Deconstruction and Reuse scenario. While close environmental impact results were recorded in modules A_4–A_5, C_1–C_4 for identical study cases with liner tray wall cladding envelope and sandwich panel envelope, a difference of 9.52–29.20 kg CO_2 eq/m^2 is registered in the Production Stage (A_1–A_3) when on an existing envelope consisting in sandwich panels is installed an additional layer of sandwich panels in order to comply with same heat transfer resistance of the façade as in the cases with liner tray cladding system.

The smallest environmental impact is shown by the case when the entire structure is built with reclaimed elements and the wall envelope is made of liner tray cladding (1171.67 t CO2 eq/m^2) while at the end-of-life of the structure the materials are recycled.

In Fig. 4 is presented a comparison of impacts computed in Module D between structures with liner tray wall cladding envelope and structures with sandwich panels envelope. The benefits are reflected in the assessment as negative values. In all cases the highest potential benefits (negative values) appear for the structures which have a liner tray wall cladding envelope, and the highest loads (positive values) appear for the structures that have sandwich panels envelope system. Differences of 8–25% in the potential benefits and 11–19% in the potential loads are shown between the two envelope solutions.

According to the results, the highest potential benefits appear in Case 0 with a Demolition and Recycle scenario in the End-of-life stage for both envelope solutions. In this situation, the maximum potential benefit is recorded for structures that have a liner tray wall cladding envelope (–140.74 t CO2 eq/m^2).

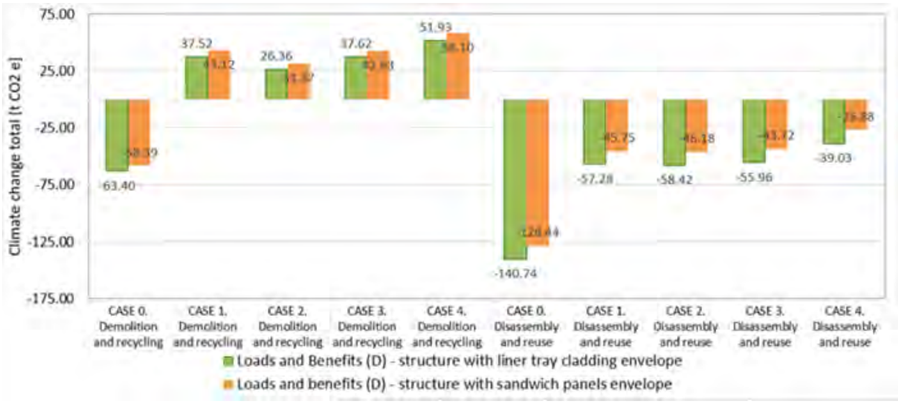

Fig. 4. Loads and benefits comparison (module D) between structures with liner tray wall cladding envelope and structures with sandwich panels envelope.

4 Conclusions

Reusing building materials and components plays an important role in reducing the need for new resources and diminishing emissions related to the extraction of raw materials, transport, and production processes. Although reused construction materials might not immediately fulfil the entire demand of new building projects, integrating highly reusable materials, such as steel, from previous use phases can substantially aid in cutting down the embodied carbon footprint of the buildings.

The material selection, energy efficiency, and durability of the building envelope can also significantly impact the environmental impact of the building. It is essential to consider the design and materials of the building envelope carefully to ensure optimal energy efficiency and environmental sustainability.

The assessment presented in the paper is based on single-storey industrial halls and compares environmental indicators of a steel structure build with new materials, a steel structure designed for disassembly and four additional cases of steel structures focused on the reuse of an existing steel structure and/or reclaim of various elements based on the same building having envelopes consisting of liner tray cladding system or sandwich panels cladding system.

The findings of the LCA reveal that the Climate Change Total is elevated when constructions are built with new materials and have liner tray wall cladding envelopes. This holds true regardless of the end-of-life scenario, primarily due to the environmental consequences associated with the steel production process and the additional effort needed for installing the liner tray built-up wall system. When structures are built with reused elements or components and have liner tray wall cladding envelope, in both End-of-Life scenario (Demolition and Recycle scenario and respectively Deconstruction and Reuse scenario) emissions are lower than those of structures built with reused elements and having sandwich panels envelope systems.

When considering different envelope solutions, the LCA results reported here confirm that the highest potential benefits (8–25% higher) appear for structures which have a liner tray wall cladding envelope, and the highest loads (11–19% higher) appear for structures which have sandwich panels envelope system.

In addition to the potential benefits of LCA, a significant benefit in using liner tray cladding systems comes from the potential for possible reuse, which is clearly superior to the potential for repeated reuse of sandwich panels, contributing to further reducing the environmental impact of a cladding system even after its second life cycle.

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Life Cycle Assessment of the Lightweight Timber Structures with Bio-Based Aggregate Composites

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Abstract. The lightweight structures play a crucial role in mitigating the environmental impact of buildings throughout their lifespan. There is an interest in exploring various agricultural by-products as effective aggregates for filling framed timber structures. Natural fibers, such as hemp shives, are gaining attention for their environmental benefits, including biodegradability, renewability, recyclability, composability, and their potential to reduce greenhouse gas emissions. By harnessing these natural fibers, it is possible to reduce emissions associated with the most popular wall structures. Moreover, this approach reduces agricultural waste and facilitates integration into a circular economy model. This study delves into the effects of bio-composites created from hemp shives, combined with starch, gypsum, and a geopolymer binder, in fabricating lightweight timber structures. These lightweight structures are compared among themselves and conventionally used wall structures, assuming one square meter of wall with a specific U-value as the comparative unit. Results from a life cycle assessment revealed that these innovative lightweight timber wall structures yield CO_2 emissions ranging from −13.94 to 82.89 kg of CO_2 equivalent per square meter. In contrast, compared to traditional brick wall constructions, these structures offer substantial savings, potentially reducing emissions by up to 149.38 kg of CO_2 equivalent per square meter. This research underscores the promising environmental advantages of utilizing natural fiber-based bio-composites in constructing lightweight timber structures, emphasizing their potential to reduce carbon footprints in building construction significantly.

Keywords: Life Cycle Assessment · Bio-Composite · Starch · Gypsum · Geopolymer · Lightweight

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1 Introduction

The building sector plays a vital role in national and international sustainability goals. According to a 2019 report by the International Energy Agency (IEA), it accounts for 36% of global final energy use and 39% of CO_2 emissions, making it one of the most significant areas of energy use and emissions [1]. In this context, the role of insulation materials has grown significantly, as they are a deciding factor in reducing the environmental impacts of buildings over their lifetime. Almost a third of all buildings in the EU are over 50 years old, and over 75% are not designed to be energy efficient. Updating or repurposing these structures can cut annual CO_2 emissions and energy use by 5–6% [2, 3].

The environmental benefits of natural fibers made from agricultural waste by-products include their biodegradability, renewability, recyclability, composability, and potential to reduce greenhouse gas emissions. Using these fibers, it is possible to reduce emissions produced by insulation materials that are in the market now, reduce agricultural waste, and make it part of a circular economy [4]. Together with a renewable construction material resource such as timber, it is possible to incorporate lightweight bio-based aggregate materials in timber frame structures effectively.

Traditional mineral binders such as Portland cement and lime are used to ensure the effective use of natural fibers in buildings [5]. However, they are associated with a high carbon footprint during their production, and therefore, alternative binders are often considered. Starch, gypsum, and geopolymer could be used as potential binders in bio-composite production [6]. Gypsum is a globally available substance primarily employed in the construction industry (plasters for renderings, plasterboards, prefabricated blocks, etc.). It is adaptable, a thermal insulator, a humidity regulator, non-combustible, and an acoustic absorber. Due to their chemical stability, gypsum materials can be fully recycled. As a result of this, researchers are interested in finding ways to use gypsum in construction sector materials to reduce existing large amounts of construction waste [7]. Starch is a biopolymer found in the photosynthetic tissues of plants that is both abundant and renewable. Starch is a cost-effective and biodegradable material with universal properties, composed primarily of amylopectin (75%) and amylose (25%). In Europe, starch is mainly extracted from potatoes, wheat, and maize. In investigations to produce thermal insulation composites, natural fibers such as hemp were combined with starch as a binder, resulting in improved mechanical performance [8]. Geopolymers have been gaining attention as an alternative to traditional cement-based materials in construction and various industrial applications. Geopolymers are inorganic polymers that can be formed from the reaction of aluminosilicate materials with an activating solution. They offer several advantages, including reduced carbon dioxide emissions, improved durability, and potentially lower production costs compared to Portland cement [9]. Many of these alternative materials have the potential to reduce the environmental footprint of construction materials, while there is a limited number of articles dedicated to ecological impact calculations.

The life cycle analysis (LCA) approach is a valuable tool for comparing the environmental performance of different insulation materials. It is consistent with the life-cycle thinking idea that should be used to ascertain the environmental consequences of insulating materials. LCA studies typically aim to either support decisions for more environmentally friendly materials or identify environmental hotspots in manufacturing building materials. Regarding materials, the goal of LCA studies is typically to support decisions for more environmentally friendly materials [3, 10].

2 Methodology

2.1 Life Cycle Assessment Application

This study aims to evaluate the environmental impact of novel bio-based insulation materials. This study performed a cradle-to-grave comparative LCA on bio-composite materials using three different binders: starch, geopolymer, and gypsum. The LCA was conducted by ISO standards 14040/44 and utilized the SimaPro 9.4 software. Most of the processes were modeled using the Ecoinvent 3.0 database, and the ReCiPe 2016 Midpoint (H) V1.07 method was used to calculate the environmental impacts.

2.2 Goal and Scope Definition

This study aims to compare the environmental impacts of the bio-based insulation materials developed in this research with traditionally used insulation materials for timber structures. The LCA results will provide insights into the overall environmental performance of the bio-based insulation materials, including potential environmental hotspots that could be targeted for further improvement.

The functional unit (FU) is the standard measurement used to compare products. Density, thickness, and thermal conductivity are three primary features and characteristics that can be used to classify insulation materials [10]. Thus, functional units were chosen to provide one square meter (m^2) of insulation board with a U-value of 0.105 W/(m^2·K). This U-value ensures normal operation in cold climates, such as Latvia. Functional units are identical for all three bio-composites thus it is possible to compare these materials.

The input data for calculations of bio-composites based on three types of alternative binders are summarized in Table 1. The production process and technological properties of the binders and bio-composites are described in the previous articles [12–14]. Cradle-to-gate system boundaries were used as the use stage is similar for all compared materials.

Table 1. Data of bio-based materials for FU [12–14]

Bio-composite	Mass of 1 m^2 of bio-composite, kg	λ_d, W/mK	L, m	Density, kg/m^3	U-value, W/(m^2·K)
With starch	161.10	0.0675	0.64	250	0.105
With gypsum	152.38	0.0640	0.61	250	0.105
With geopolymer	151.63	0.0610	0.58	261	0.105

2.3 Life Cycle Inventory

Data shown in tables are normalized according to FU before putting in SimaPro. Production of hemp shives was used from a study developed before [5]. Inputs in SimaPro for bio-composites are shown in Table 2.

Table 2. Quantities of material and energy inputs as referred to in the FU of the study (1 m^2 of composite with U-value 0.105 W/(m^2·K)), in each of the three different bio-composites.

Input items	Quantity per declared unit		
	Starch bio-composite	Gypsum bio-composite	Geopolymer bio-composite
Hemp shives, kg	129.86	74.36	117.35
Water, kg	190.29	195.05	117.35
Potato starch, kg	34.22		
Glycerol, kg	13.56		
Na_2SiO_3, kg	12.21		
Gypsum, kg	–	91.43	
Metakaolin, kg	–		205.37
Alkaline solution, kg	–		29.34
Electricity, kWh	78.59	42.46	63.77

For comparison with traditional materials, a wooden frame (see Table 3) was added for all three bio-composites. Traditional materials for comparison were chosen from studies developed before [16]. Additionally, all materials were also compared to standard wooden structures. The composition of the standard wooden structure is shown in Table 3.

Table 3. Quantities of material and energy inputs as referred to in the FU of the study (1 m^2 of composite with U-value 0.105 W/(m^2·K)), for standard timber structure

Input items	Value	Comments
Wood, m^3	0.05	Wooden frame
Screws, kg	0.25	Wooden frame
Tyvek Housewrap, kg	0.09	Standard wooden structure

(*continued*)

Table 3. (*continued*)

Input items	Value	Comments
Gypsum board - 9 mm, kg	5.90	Standard wooden structure
Thermal insulation (Knauf TP115) – 250 mm, kg	12.50	Standard wooden structure
Vapor barrier ELTETE ELT-PEFOIL 200, kg	0.16	Standard wooden structure
Thermal insulation (Knauf TP115) – 50 mm, kg	5.00	Standard wooden structure
Oriented strand board – 10 mm, kg	7.00	Standard wooden structure
Gypsum board GKB – 12.5 mm	8.20	Standard wooden structure

3 Result and Discussion

The results are examined individually for each type of bio-composite, analyzing separate impact categories of materials to assess which one has the greatest influence. Subsequently, all bio-composites and the whole assembly for one functional unit (FU) are compared with traditional timber frame constructions and insulated block materials.

The global warming impact category result for the bio-composite with starch is 79.23 kg CO_2 eq. (refer to Fig. 1). The materials causing the most significant impact in the bio-composite are potato starch (56.12 kg CO_2 eq.), glycerol (48.76 kg CO_2 eq.), and electricity (43.42 kg CO_2 eq.). In the production of bio-composite in a laboratory setting, electricity stands out as one of the significant contributors. However, in industrial production, the result would likely be considerably lower.

Hemp shives capture CO_2 during growth, resulting in a negative impact in the global warming potential category, thereby improving the overall result of the bio-composite. Among the components, potato starch contributes most significantly to the impact categories. To diminish the impact of potato starch, considering the use of starch from alternative sources could be beneficial. Starch is obtainable from the food industry as food waste, agricultural by-products, and other sources. Utilizing starch recovered from food waste could notably decrease the impact of the bio-based composite across various LCA categories, contributing to its integration into the circular economy and promoting sustainability [15].

The composition of the starch bio-composite is not optimized to reduce its environmental impact but rather crafted to achieve maximum strength parameters. Considering the obtained results, it is possible to optimize the quantity of added additives (such as sodium silicate and glycerol) since reducing them could lower the material's overall environmental impact significantly without adversely affecting its functional properties.

Gypsum is a mineral binder with a relatively small carbon footprint; it generates only 0.098 kg/CO_2 eq. Compared to 0.857 kg/CO_2 eq. For Portland cement per 1 kg of binder [Ecoinvent database]. Hence, the overall environmental impact of the bio-composite is negative because the binder has a minimal environmental impact of –17.59 kg CO_2 eq. (refer to Fig. 2). This stands as one of the significant benefits of using gypsum binders.

As the filler used, hemp shives absorb CO_2 during their growth period, which results in a negative overall carbon footprint for the bio-composite. It absorbs more CO_2 than is

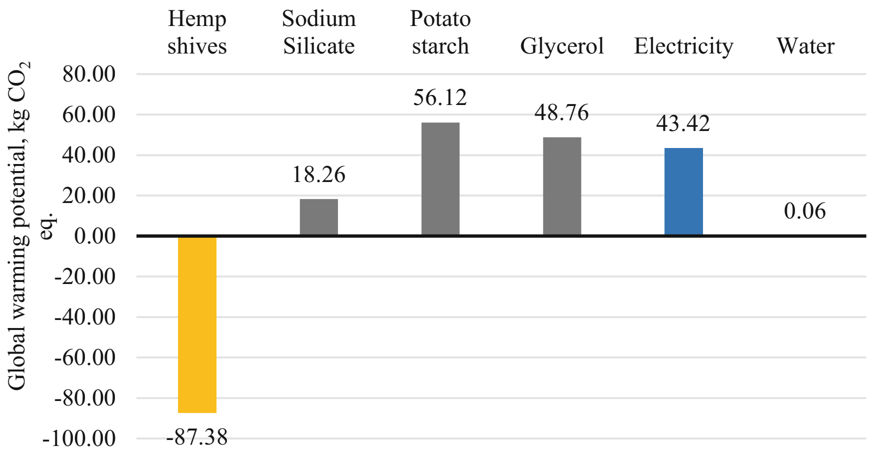

Fig. 1. LCA results in global warming impact category for bio-composite with starch.

emitted during its manufacturing process. This is also related to the fact that there are not many additional substances in its composition; other emissions come from electricity usage during material production and drying processes.

Nevertheless, improvements could also be made in the composition, especially concerning the binders, because gypsum is relatively easily recyclable and available as a waste product. For instance, they are using recycled construction gypsum or phosphogypsum, which arises during the production of fertilizers. If directly used from the fertilizer production line, emissions related to gypsum could be entirely eliminated as there would be no need for additional incineration processes [16].

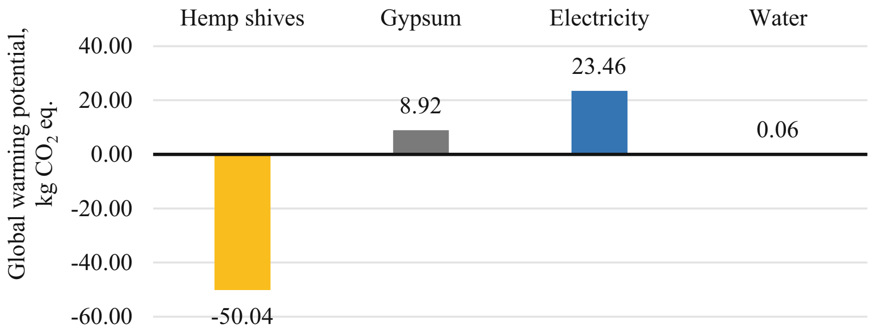

Fig. 2. LCA results in global warming impact category for bio-composite with gypsum.

The highest impact among the examined experimental materials is the bio-composite material with geopolymer, which amounts to 64.49 kg CO_2 eq. Per functional unit (FU) (refer to Fig. 3). The primary contributor in this case is metakaolin, as anticipated based on the literature review [17]. Metakaolin alone generates 99.63 kg CO_2 eq., surpassing the material's impact itself; the hemp shives and their captured CO_2 mitigate the overall impact of the material. However, the impact of the alkaline solution and electricity is also notably high.

To reduce the environmental impact of geopolymers, it could be possible to use waste products such as fly ash, which have a significantly lower environmental impact compared to metakaolin [17]. Yet, this substitution would significantly affect the rest of the composition and the desired properties, making such a replacement more complex. However, in further research, an in-depth analysis should be conducted regarding the increased utilization of waste products in these geopolymer-based bio-composites.

The traditional building materials considered in this study encompass aerated concrete blocks, expanded clay cement, and clay ceramic blocks insulated with either stone wool or polystyrene foam. These brick constructions are more prevalent than new material systems, primarily employed in private house construction [16]. Six functional units were constructed using these materials, with each brick material insulated using either of the two insulation materials. All functional units maintain an identical U-value of U = 0.105 W/(m^2·K) as used in this study. The finishing layers across all types remain consistent without facade cladding and internal render.

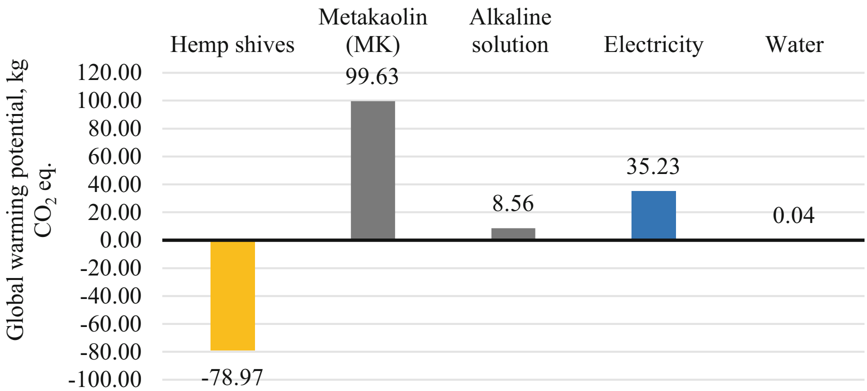

Fig. 3. LCA results in global warming impact category for bio-composite with geopolymer.

Among all materials, bio-composites with gypsum exhibit the most favorable results since they are the only materials that capture more CO_2 than they produce, amounting to −13.94 kg CO_2 eq. Walls constructed from various brick materials generate significantly more CO_2 (up to 136 kg CO_2 eq.) compared to traditional timber construction per square meter (32.18 kg CO_2 eq.). This discrepancy primarily arises due to the substantial quantity of material used in brick block production, which also contributes to their greater mass, ensuring heightened thermal inertia. However, this advantage diminishes compared to the developed materials, as they possess relatively high thermal inertia. This characteristic stems from both the fillers and the binders used.

The traditional timber frame construction shows higher results than the gypsum bio-composite with a timber frame, and these results are generally lower than traditional masonry constructions. However, it should also be noted that the composition of the gypsum bio-composite could be improved to reduce its impact on the environment further, for example, by replacing gypsum made from fresh raw materials with phosphogypsum.

If these same exterior walls of the building were made from the developed gypsum bio-composite, which sequesters −13.94 kg CO_2 eq. per square meter. Thus, by choosing the gypsum bio-composites developed in the project and replacing the exterior walls of an average private house with these materials, it is possible to save 149.38 kg CO_2 eq. per square meter. Exterior walls typically account for 15 to 20% of total embodied carbon emissions, so it can be concluded that by using one of the materials developed in the project, the building's total embodied carbon can be reduced by approximately 20%. It should be noted that these materials can also be used for interior wall construction, and by changing the composition, they can also be used for underfloor and roof insulation. This would allow for even greater CO_2 savings (Fig. 4).

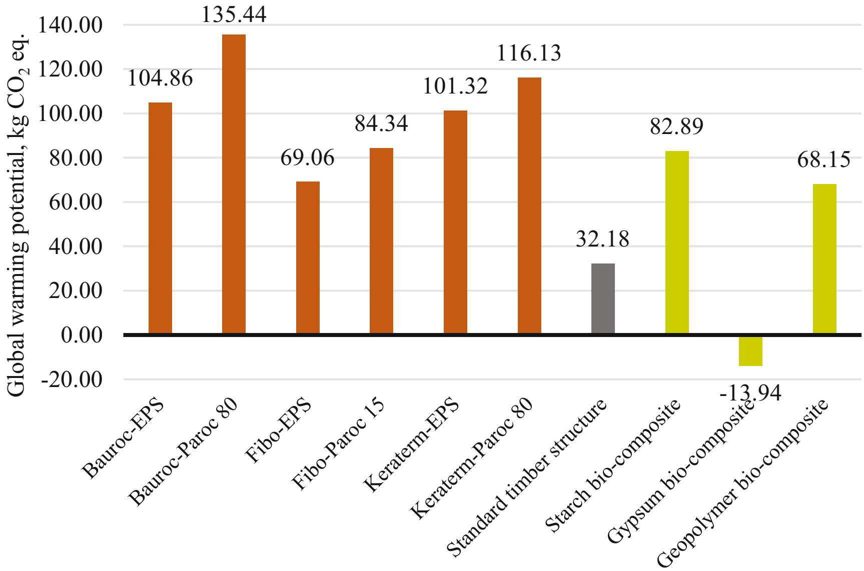

Fig. 4. LCA results for comparison of insulation materials in wooden frame with traditional building materials.

4 Conclusion

Three types of bio-composites made from different binders, gypsum, geopolymer, and starch, were examined. The materials were compared to each other and to traditionally used insulation materials with timber frame construction, assuming one square meter of wall with a specific U-value as the comparative unit. Similarly, all materials were compared to different traditional construction types with brick blocks and various insulation materials.

Bio-composites that use starch as a binder have a relatively high environmental impact, 82.89 kg CO_2 eq. per m^2 of wall. The most significant impact comes from the use of potato starch as a binder, as well as from the addition of glycerin and electricity required for the curing of bio-composites. To improve the environmental impact of this material, it would be possible to use a composition with reduced starch content, reduce the use of additives, or use starch from other raw materials.

Geopolymer bio-composites have slightly better results than starch bio-composites but are still relatively high, producing 68.15 kg CO_2 eq. per square meter of wall. The main impact in the case of geopolymers comes from the use of metakaolin and the electricity required for curing. However, like with starch bio-composites, it is possible to improve the material's impact on the environment by reducing the use of additives, choosing alternative raw materials, and optimizing the curing process.

Gypsum bio-composites show the best results in terms of environmental impact, as they are capable of storing 13.94 kg CO_2 eq. per square meter. This is mainly due to the low environmental impact of gypsum as a binder and the low drying temperature required. However, the environmental impact of gypsum can be further reduced by using phosphogypsum or recycled gypsum.

Results from this study show that all three developed bio-composites show a more negligible impact on the environment in the global warming impact category than traditional building materials. However, compared to standard timber structures, the only bio-composite with a lower impact on the environment is with gypsum binder. Geopolymer and starch binder bio-composites show a higher impact than standard timber structures, although it is worth noting that these bio-composites are produced on a small scale, which outputs a higher impact from energy consumption.

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Circular Economy of Wind Turbines Waste in Constructions and Cities

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Abstract. Wind energy is one of the most widely distributed renewable energy sources. Generally, wind turbines have an expected lifetime of 20–25 years after which decommissioning is expected. Life cycle assessments show that optimal recycling at the end of life is of economic and environmental interest and is in line with the principles of a circular economy. Despite these benefits, current recycling processes cannot guarantee high-end material quality, but the reuse of parts of wind turbines as construction elements in buildings and infrastructures has been demonstrated to be a suitable option. This study presents an overview of wind power installations in Europe, emphasizing the typology of farms, onshore and offshore, and trends of the wind industry that promote an increase in the size and power of wind turbines. The study aims to make it clear how the different types of materials used in wind turbines, such as steel, iron, aluminium, copper, polymers, glass and carbon fibres, change according to the development of the technology. Moreover, examples of reusing wind turbine components in cities and buildings are collected and illustrated to provide a panorama of the potential for the reuse of these components in the concept of a circular economy in the construction sector.

Keywords: Circular economy · Wind energy · Wind turbines · Buildings · Constructions

1 Introduction

1.1 Wind Farms Installation in Europe

The wind energy market is growing in Europe, making wind turbine waste significant in quantity and of importance in future scenarios of circular economy. It is crucial to understand how and where wind technology was and is spreading in order to locate potential sources of materials to be collected, treated and reused. The typology and quality of materials also require attention, especially if they will be addressed to the construction sector.

In 2022, the total installed wind power capacity in Europe amounted to 255 GW, mainly attributable to onshore plants (88%) [1]. But in the decade 2013–2022, offshore installations recorded an annual growth rate of 15.7%, higher than onshore farms (7%).

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Two-thirds of the total wind capacity is installed in six countries, such as Germany (66 GW), Spain (30 GW), the United Kingdom (29 GW), France (21 GW), Sweden (15 GW), and Turkey (12 GW) [2].

The 67% of onshore wind capacity is installed in seven countries: Germany (58.95 GW), Spain (29.8 GW), France (20.65 GW), United Kingdom (14.6 GW), Sweden (14.4 GW), and Turkey (12 GW). Significant shares come from Italy (11.8 GW), Poland (7.86 GW), the Netherlands (6.22 GW), Portugal (5.67 GW), Finland (5.60 GW), Denmark (4.97 GW), Greece (4.8 GW) and Ireland (4.61GW) [1].

Offshore wind capacity counts 30.1 GW, of which 97% is installed in five countries: the United Kingdom (13.9 GW), Germany (8.0 GW), the Netherlands (2.8 GW), Denmark (2.3 GW) and Belgium (2.2 GW). The remaining 3% share is distributed in other European countries, among which France (0.48 GW) and Sweden (0.19 GW) stand out [1, 2]. Figure 1 shows the percentages of installed wind power capacity in the European countries.

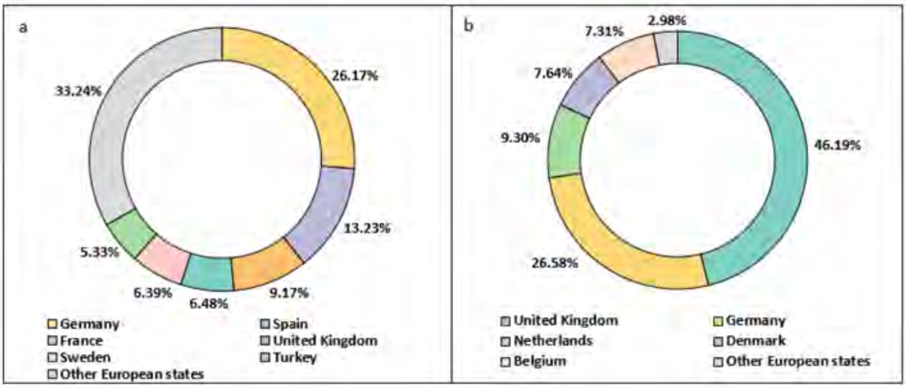

Fig. 1. European countries with the highest share of wind power: (a) onshore; (b) offshore.

Taking into account wind generators, the nominal capacity increased by an annual average of 5.50% for onshore and 7.45% for offshore turbines. This trend highlights how wind turbines are getting larger and larger and more powerful. Sweden and Finland have the most powerful onshore wind turbines, with an average capacity of 5.7 MW and 5.6 MW, respectively. The lowest average capacity is held by Portugal (2.2 MW) and Poland (2.8 MW) [1].

Moreover, knowing the year of installation of wind turbines is a critical information to manage their life cycle and to estimate the amount of waste to be disposed of. More and more wind farms in Europe are reaching the end of their life cycle. In 2022, 14 GW of wind farms were nearing the end of life (EoL) and about 78 GW will reach 20 years of age in 2030. The oldest wind turbines are installed in Spain with an average age of 13.4 years, followed by Portugal (13.3 years), Italy (11.4 years), Germany (11.3 years), the UK (8.7 years), and France (8.0 years) [1]. The decommissioning of air generators is a challenge for the future. The study presented in [3] predicts that Germany will be the largest producer of onshore wind waste in 2050, with an estimated 67.6 tons of wind turbine blades to be disposed of. Sweden, the United Kingdom, Ireland, Italy, and Eastern Europe will follow with a significant amount of waste. A moderate increase is expected in Spain, France, Finland and central Greece, while a slight increase is predicted in the Baltics, northern UK, northern France, and Poland. The UK is projected to become the largest producer of offshore wind waste by 2050 with a waste generation rate of approximately 40%. The Netherlands is predicted to record the second largest production rate of 8%, followed by Belgium (5%) and Ireland (2%).

1.2 Potentialities of Wind Energy in Circular Economy and Constructions

Life cycle assessments (LCAs) demonstrated that the materials used for the manufacture of turbines constitute 70–80% of the impact. As a consequence, an effective recycling at EoL can provide economic and environmental benefits.

In particular, the study conducted in [4] considered a cradle-to-gate life cycle inventory analysis of materials of a 60 MW wind park. The saved energy was estimated to be approximately 81 TJ, and the reduction in emissions equal to 7351 tons of CO_2.

Moreover, LCA analyses demonstrated that 342 kg of CO_2 can be saved for every tonne of blade waste used. Substitution of blades of steel and concrete products was found to provide the most impacts [5].

Despite the clear benefits, the recycling of composite materials from wind turbines requires high costs and limited volumes of waste are available. Repurposing blades into second life structures appears an increasing and suitable alternative, but difficulties occur: a perceived lower quality of used materials, uncertainty on residual structural properties, lack of end markets for recycled materials [6]. In addition, it should be considered that wind turbines use rare earth components in depletion and their recovery could be of significant importance [7].

1.3 Aim of the Study and Methodological Note

The aim of this paper is to illustrate the state-of-the-art in how wind turbines components can be reused in urban environments and buildings following the concept of a circular economy and sustainable energy transition.

In particular, the research questions that inspired the study are:

- what are the potentialities of wind turbines materials to be applied in the circular economy of buildings?
- are there applications developed in research or on-site that constitute reference examples?

For answering these questions, the information presented was extracted from a collection of documents merging different sources: journal and conference papers from the Scopus database, reports and websites of European institutions, and datasheets of companies. The variety of the documentation allows a larger view of the topic considering both the scientific developments and the real case studies.

2 Materials from Wind Turbines

A wind turbine is basically made up of a foundation, a lattice or tubular tower, a generator (or nacelle), and blades. These components include numerous materials:

- Fiberglass or carbon fibre reinforced composites are commonly used for turbine blades due to their strength, flexibility, and lightweight properties;
- Steel is a common material for wind turbine towers, providing the necessary strength to support turbine components;
- Steel and alloys are often used for gearbox and generator components because of their durability and ability to withstand mechanical stress;
- The nacelle, which houses the turbine gearbox and generator, is typically made of steel or aluminium.

According to a report from the National Renewable Energy Laboratory [8], the composition of wind turbines varies based on their make and model. Generally, wind turbines consist mainly of steel, representing 66–79% of the total turbine mass. Other important components include fiberglass, resin, or plastic (11–16%); iron or cast iron (5–17%); copper (1%); and aluminium (0–2%).

Wind turbine blades are considered attractive components that can be reused in the construction sector due to their valuable mechanical and durability properties [9].

Moreover, ongoing research focuses on developing advanced materials to enhance the efficiency and durability of wind turbines. Innovations include the use of new alloys, hybrid materials, and smart materials that can respond to changing conditions.

The authors collected data provided by Vestas company, a global leader in the design, manufacture, and sale of wind turbines [10]. The company is committed to reducing the environmental impact of its products and provides, for 20 onshore and 3 offshore wind turbine models, the percentages of the materials used [11]. These data were used to make it clear how different types of materials, such as steel, iron, aluminium, copper, polymers, glass and carbon fibres, change according to the turbine capacity. The analysis excluded electrical and electronic components, lubricants, and fluids due to minor interest in constructions and cities. Figure 2 shows the percentages of materials used in onshore and offshore wind turbines.

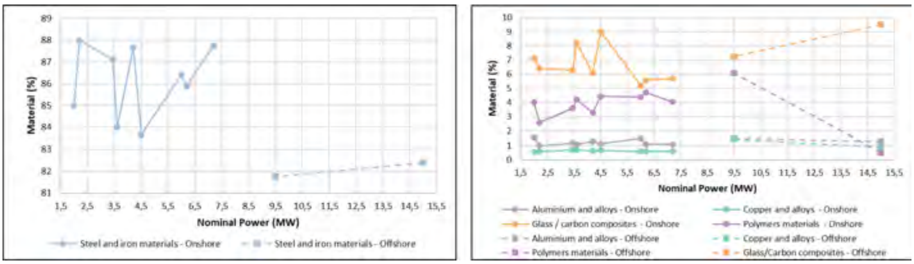

Fig. 2. Percentages of materials used in the construction of onshore and offshore wind turbines. Source Vestas [11].

Steel and iron materials are the most used materials in both onshore (83% to 88% by weight) and offshore wind turbines (about 82%). Aluminium and alloys account for 1–2% of offshore wind turbines. The 2 MW turbine has an aluminium percentage of 1.57%, whereas turbines with higher rated power, with the exception of the 6 MW turbine (1.50%), have values below 1.50%. For offshore wind turbines, aluminium and alloys vary between 1.3%–1.5%. The amount of copper and alloys used in onshore wind turbines varies between 0.57% and 0.60%. In offshore wind turbines, the amount of copper decreases with the capacity (from 1.45% to 0.90%). Onshore wind turbines contain a percentage of polymeric materials (epoxy resins, glass and carbon fibres, and thermoplastic polymers) that varies between 2.60% and 4.70%. This value varies according to the rated power of the turbine; in fact, the 2 MW turbine has a percentage of polymeric materials of 4%, similar to the 7 MW turbine (4.05%). Offshore wind turbines, on the other hand, have a percentage of polymeric materials of 1.45% for 7 MW turbines and a value of 0.90% for the 15 MW turbine. On average, the amount of glass/carbon composite materials vary between 6.0% and 9.0% in onshore wind turbines and between 7.25% (9 MW) and 9.5% (15 MW) in offshore wind turbines.

Upon concluding its intended operational lifespan, a wind farm developer faces the task of choosing among various alternatives for the aged facility, i.e. extending its lifetime, opting for repowering (partial of full repowering), or proceeding with decommissioning (reuse, recycle, incinerate, landfilled). The determination of the most appropriate action is influenced by technical, economic, and regulatory considerations.

Additionally, efforts are being made to repurpose entire turbine blades as structural components in various applications. These applications range from bike sheds in Denmark, noise barriers for highways in the US, and 'glamping pods' scattered throughout festival sites in Europe to their incorporation into civil engineering projects like pedestrian footbridges in Ireland [12].

3 Reusing of Wind Turbines in Constructions

Current recycling processes for fibre-reinforced polymers cannot provide high-quality materials. It seems more viable reusing segmented parts of turbines as construction elements. Moreover, reflection on the consequences for the initial design of composite products is still missing [13].

The combination of fibres and polymers, also known as glass fibre reinforced polymer (GFRP) composites, represents the majority of the material composition of the blades (60–70% reinforcing fibres and 30–40% resin by weight) [5].

3.1 Wind Turbines Reuse in Cities

Examples of recycling of wind turbines in urban environment are increasing. The information collected by the authors demonstrates that blades and towers can be included in infrastructures such as bridges, barriers with different functionalities, and urban and domestic furniture [13, 14].

Pedestrian, bicycle, and vehicle bridges that use wind turbine blades as their primary load-carrying structural members are evaluated in the project "Re-wind Network blade repurposing solutions" [15].

The Re-Wind Network repurposed wind blades as poles of different types:

- Power line poles for distribution and transmission lines;
- Cell phone towers;
- Lighting poles;
- Sign support poles.

Depending on the size of the wind turbine blade, they can be used in urban or suburban neighbourhoods.

Barrier structures designed from wind blades can perform various uses:

- construction site boundary barriers;
- noise barrier;
- traffic barrier (Jersey barrier).

These constructions can also be used for wave and wind attenuating and seawall barriers. Barrier dimensions vary depending on the size of the blades and design requirements to replace timber or steel and save material (see Fig. 3).

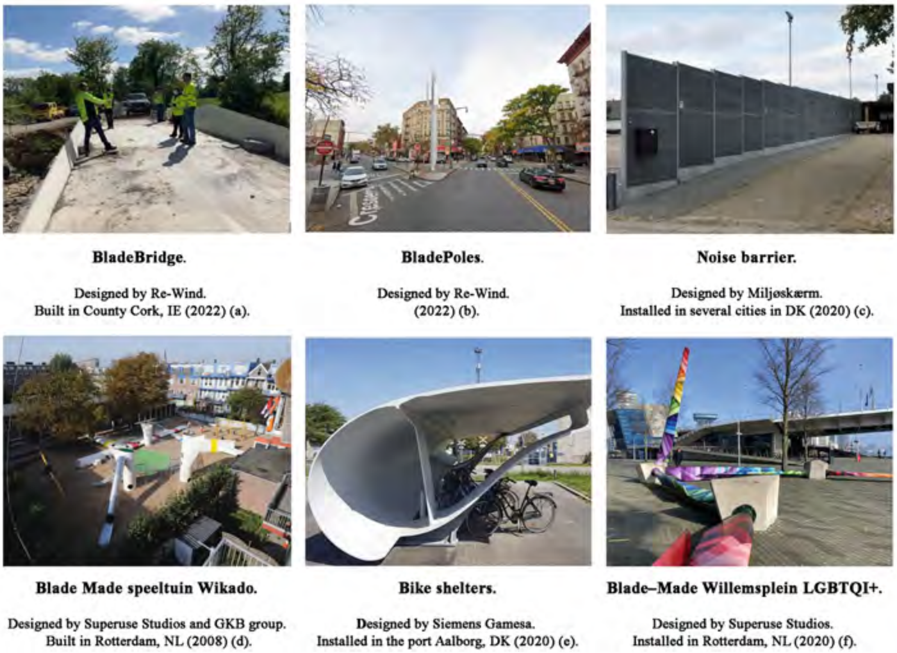

Fig. 3. Examples of reuse of wind turbines in urban environment. Sources: (a) and (b) from [15], (c) from [16], (d) from [17], (e) from [22], (f) from [23].

Noise attenuation barriers made of recycled fiberglass are proposed by the Danish company Miljøskærm [16]. A section of the wind turbine blade would be used as small grain partition walls, replacing concrete walls, or as traffic barriers [6]. Superuse Studios Rotterdam designed playground blades [17, 18] and street furniture [19] using discarded wind turbines. Turbine blades are also used for bus and bike shade, canopies, roofing parking-lot. Bike shade installations are well located in Aalborg and Almere Port (Denmark). The installations were promoted by Siemens Gamesa Renewable Energy S.A [20] and Superuse Studio [21].

3.2 Wind Turbines Reuse in Buildings

Decommissioned wind turbines can also be transformed into building components. According to the study conducted in [24], developing projects to reuse disused wind turbines could benefit the coastal areas in Mexico's Yucatan province (see Fig. 4). The homes of the region, built with low-quality masonry blocks, are vulnerable to hurricanes and severe flooding. The reuse of wind turbine blades, both intact and dissected, assumes a key role in the enhancement of these components in the structural field, helping to meet the challenges associated with extreme weather events. The study considered a 2 MW wind turbine blade, representative of the technology of the 2000s, and proposed an innovative solution consisting of raising the houses with the section of the wind turbine closest to the hub, appropriately cut into segments suitable for the size of domestic houses. The sections can be cylindrical or elliptical, and installed in the ground and filled internally with rubble.

Fig. 4. Examples of reuse of wind turbines in buildings structure. Sources: (a) from [24], (b), (c), (d) from [15].

Other solutions are offered by Re-Wind Design [15] (see Fig. 4). The company made the idea of construction of small shelters including blades of wind turbines that have reached the EoL. Shelters can be arranged on prefabricated containers and used for both domestic and industrial use. Another use is to build fixed camping tents called Glamping Pods using the wind blades as a wall or roof because of they are stronger and have a longer life span than wooden trusses or sheet metal.

3.3 Repowering of Wind Turbines

Repowering involves replacing or upgrading older turbines with newer, more efficient models. This may include using advanced technology, larger rotor blades, and more powerful generators. Repowering can significantly increase the overall energy production capacity of a wind farm and improve its economic viability. It also contributes to technological advancements in the industry.

Repowering offers numerous advantages, including a nearly three-time increase in the electricity output of a wind farm, achieved with a 25% reduction in the number of turbines on the same site. Older wind farms, typically located in ideal locations, often feature less efficient turbines. Upgrading to more powerful turbines makes logical sense. Additionally, repowering allows local communities to continue to maintain the benefits of their wind farm, such as local taxes and community projects.

Repowering wind turbines requires checking components that will not be replaced. It is important to evaluate these components if they are to stay in service with the repowered turbine. There are several challenges to be considered here regarding the structural components of wind turbines. In general, towers and foundations are over designed and have a high safety factor. However, it is necessary to evaluate the remaining useful life, including fatigue analysis, serviceability and strength. Blades can contain cracking and pitting of the leading edge of the blade. In the case of tower bed frames, this is a high-cost item and often the last item to wear out.

An interesting example considering repowering is the CRAIL Wind Project [25], which illustrates how repowering can be successfully executed with attention to regulatory compliance, technical expertise, comprehensive services, and long-term support. By repurposing an existing turbine and adapting it to current standards, the project contributes to sustainable energy initiatives while fostering community participation and long-term environmental benefits. The refurbishment process, overseen by former Vestas engineers, encompassed a complete disassembly, meticulous inspection of all components, and refurbishment in strict adherence to the original manufacturers' specifications and tolerances. As part of this process, the turbine height was reduced from 45 to 35 m to comply with planning permission requirements. Additionally, the turbine's power output was derated from 500 kW to 400 kW to comply with limitations imposed by grid connections. Beyond the refurbishment itself, the supplier not only delivered, but also handled the construction and commissioning of the turbine. The supplier also demonstrated commitment by providing a 5-year warranty, coupled with a 5-year operations and maintenance agreement for ongoing support.

Another successful example is in Germany, such as the Düngstrup Wind Farm in Lower Saxony, where eight 1,3 MW turbines were replaced by four new 3 MW turbines on the same site [26]. While the old wind farm produced 12 GW hours per year, the new turbines produce 35 GW hours. In general, repowering initiatives are expected to increase power output four times and three times in terms of installed capacity.

4 Conclusions

The production of waste from wind farms is estimated to be growing. From the analysis performed, we can state that the materials used in the design phase will also change varying the power of onshore and offshore wind turbines. In particular, copper or polymeric materials record a higher percentage of weight in offshore wind turbines.

Current recycling processes are unable to provide high quality materials, and the reuse of segmented parts of EoL products as construction elements has been demonstrated to provide effective alternatives.

Several companies and design studios proposed and built examples of small infrastructures in urban environments, and also researchers conceptualised possible integrations of wind turbine sections as a part of buildings, such as roofs and foundations.

In summary, wind farm developers should weigh several options for aging facilities, including extending their operational lifespan, considering either partial or full repowering, or choosing decommissioning with subsequent actions such as reuse, recycling, incineration, or landfill disposal.

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Standards and Regulations

The Effect of Standardization on the Future of Sustainable Refurbishment of Existing Buildings

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Abstract. There is a vast building stock of existing buildings and the exchange rate is low (up to 0.2% per year). Therefore, there is a very strong need to deal with the existing building stock in respect to circularity. The effect of (new) regulations and standards on this volume for refurbishment and recycling of building materials is therefore crucial to meet the targets of CO2 reduction by increasing aspects of circularity overall to support environmental sustainability. The influence of standards towards the harmonization of technical requirements for refurbishment of existing buildings is therefore essential for wider implementation and acceptance in the market. There is, however, a gap identified between existing relevant standardization efforts and research in the field of refurbishment in the context of circularity. The effect of newly released standards and regulation will be analysed and identified barriers are discussed such as the generation and dissemination process of these standards.

Keywords: Standardization · Circular Economy · Existing Building · Sustainable Refurbishment · Material Passport · Building Passport

1 Introduction

In the context of the escalating global imperative to address climate change and environmental sustainability, decarbonization by 2050 constitutes a central focus within the European Union's overarching strategies for the upcoming years [1]. A central aspect to reach these goals is the strategy of Circular Economy (CE), which intends to reduce the use of primary resources by maximizing recycling and renovation in the building sector. The conversion of buildings for a different use, the partial reuse of building elements, and the recycling of materials, where appropriate, are the crucial elements in this proposed strategy. This initiative aligns with the objectives of the European Green Deal and the 2030 Agenda for Sustainable Development. The construction sector stands as one of the largest consumers of energy and is accountable for 40% of global CO2 emissions [2], along with being responsible for 60% of the global consumption of raw materials [3]. Despite the significant impact of this sector on both energy consumption and raw

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material use, there is a pressing need to accelerate building renovations. Current rates of energy renovations in the European Union (EU) hover around a mere 0.2% on average. In contrast, the EU has set ambitious targets to double these figures by 2030, also fostering deep renovations [4]. In this context, the present study focuses the vast building stock of existing buildings. The exchange rate is low (up to 0.2% per year). The effect of (new) regulations and standards on this volume for refurbishment and recycling of building materials is therefore crucial to meet the targets of CO2 reduction by increasing aspects of circularity overall to support environmental sustainability. The influence of evolving standards towards the harmonization of technical requirements for refurbishment of existing buildings is therefore essential for a wider implementation and acceptance in the market. The novelty of this paper is the analysis of the current and emerging standards in the context of refurbishment and the gap identified towards a link between research in the relevant field and the generation and dissemination process of relevant standards. The study is intended to flag the gap and barriers and builds upon a thorough examination of existing and evolving standardization efforts on national and international levels for refurbishment, reuse of existing building and recycling of building material.

2 Methodology

The research aims to identify regulations in the context of existing buildings for sustainable refurbishment and to discuss the relevance for research in the field. To reach this objective, the study conducts a comprehensive analysis of relevant standards and frameworks in the field in relation to existing state-of-the-art concepts for refurbishment and the water fall model for material reuse. The prime focus of this paper is the effect of new released standards and regulation in connection with the sustainable refurbishment of existing buildings. It imposes 6 stages from (0) Establish brief of the object of the assessment to (1) Evaluating the building to (2) Sustainable deconstruction, (3) Sustainable construction process, (4) Sustainable commissioning and (5) Sustainable in use. The discussion section describes multidimensional barriers that hinder the widespread adoption of relevant standards and identifies potential challenges, opportunities, and future prospects to better bridge the gap between research and regulation. It contributes to a more thorough understanding of the role standardization and how research can advance circularity in the building sector by tackling aspects in standardization.

3 Relevant Existing Standards for Circular Building Refurbishment

The influence of standards towards the harmonization of technical requirements in the use for building in particular has been relevant. For example, the framework for the EPBD and its recast had a strong effect on harmonizing the key building energy figures, and resulted in an usable building passport [5].

The material passport, another example, has been targeted by ISO 37101 (Sustainable development in communities - Management system for sustainable development - Requirements with guidance for use) with the aim to assess the performance. However, this is done on a general level and a clear metric for indexing of materials is not presented. Current regulation and legislation bodies of the EU have defaulted to naming convention "product passport". The Eco design for Sustainable Products Regulation (ESPR) identifies a Digital Product Passport (DPP) as key for enhancing the traceability of products and their components. However, these Passports [6] will be targeted at products and is not fully able to cover the aspect of building materials and its indexing. As reference for circularity in the building industry, the Standard new EN 17680 (European Standard: Sustainability of construction works - Evaluation of the potential for sustainable refurbishment of buildings 17680) will provide a system for the sustainability assessment of buildings using a life cycle approach.

The material passport has been targeted by ISO 37101 (Sustainable development in communities - Management system for sustainable development - Requirements with guidance for use) with the aim to assess the performance. However, this is done on a general level and a clear metric for indexing of materials is not presented.

As reference for circularity in the building industry, various new developed regulations will provide a system for the sustainability assessment of buildings using a life cycle approach and specification for the use of indicators.

One of the most recent developments is the recast of the CEN/TR 17680 Sustainability of construction works - Evaluation of the potential for sustainable refurbishment of buildings [7]. It is formally approved in 2023 (1.12.2023 in Austria for example) and is therefore relevant and can be considered formally in the rank of state-of–the-art for sustainable refurbishment of buildings.

The regulation starts with a framework (Fig. 1) to position the various standards in the context of sustainability of buildings and positions the assessment of options for sustainable refurbishment on the level executed of work, in contrast to the product level of building materials such as environmental product declarations (e.g.: EN 15804 + A2).

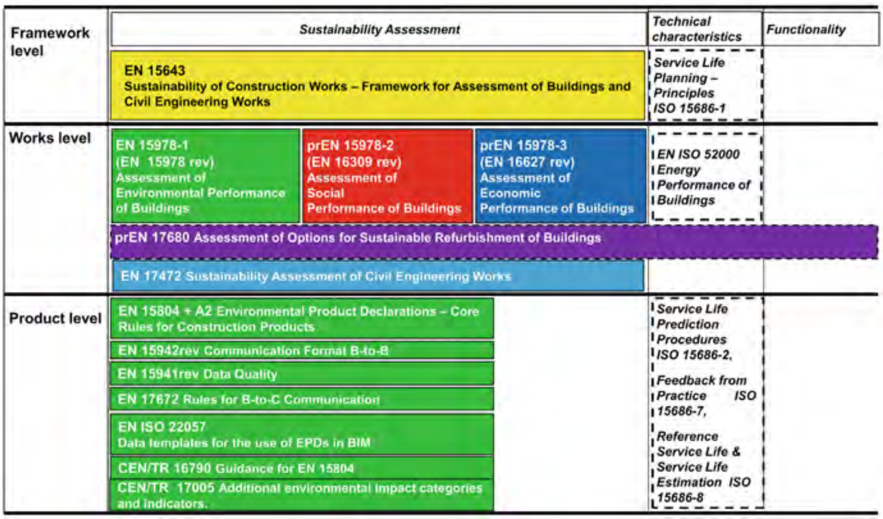

Fig. 1. Framework standards for sustainability of buildings.

The regulation intends to provide a 6-step process for application (0–6): from (0) Establish brief of the object of the assessment to (1) Evaluating the building to (2) Sustainable deconstruction, (3) Sustainable construction process, (4) Sustainable commissioning and (5) Sustainable in use are proposed. It is targeted at stakeholders at all instances that are using and running a building including facility management. It even includes visitors for some buildings as users and potential stakeholders. The standard continues to provide a strategy and methodology for sustainable refurbishment of an existing building and the evaluation of the potential of sustainable refurbishment, as a means of contributes to the circular economy to support the decision-making process (Fig. 2).

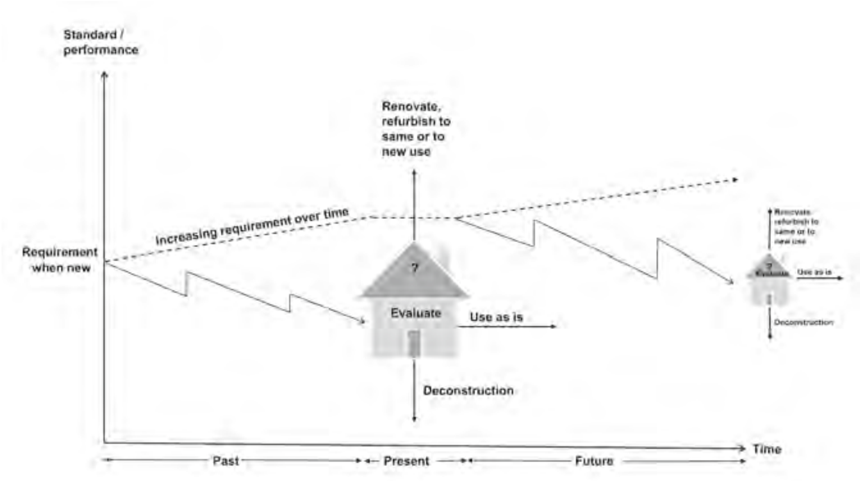

Fig. 2. Decision making process.

It starts with a decision-making process to decide about renovation, refurbishment to the same use or for a new use. The options are whether to sustainably deconstruct, use as is or refurbish for same use or other use based on the evaluation of technical and environmental condition, usability and adaptability.

The performance of the building should be evaluated in respect to current and future needs [7]. In order to meet the requirement of recorded performance levels, existing conditions and performance needs to be assessed and evaluated according to a structured decision methodology (Fig. 3) to meet planned sustainable performance targets.

These goals are divided into economic, social and environmental targets.

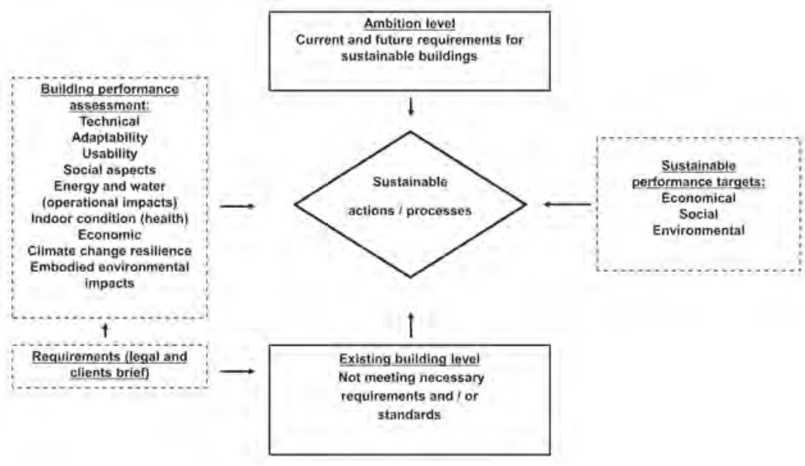

Fig. 3. Decision methodology.

The aim of Sustainable refurbishment is to "move" buildings, part of a building or portfolio of buildings into an improved area within the matrix, as shown in Fig. 4, by improving usability due to satisfactory adaptability.

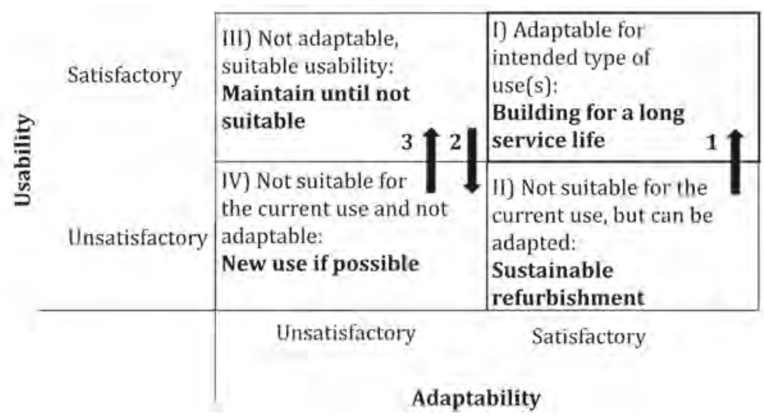

Fig. 4. Overall assessment of the building.

The CEN/TR 17680 regulation continues to provide a high level decision flow chart and presents a general procedure for the assessment to determine the achieved level of performance and condition of the building.

This study wants to focus on the consequence of this proposed assessment procedure in the CEN/TR 17680 regulation.

The standard provides a classification for the consequences in grade classes from 0 (No action necessary), 1 (Minor and medium action necessary), 2 (Essential action necessary can come in near future) to 3 (Major and serious action necessary).

These grad classes are linked to priority classes, priority action and action type to be taken. However, most of these proposed actions result in a cluster of repair, replacement and upgrade. The documents continue to recommend, that final decision on action shall be made on a building level or at an overarching, general level.

As a consequence, the document provides a matrix for a list of indicators for early decision-making in the refurbishment process in nine different categories from technical, adaptability, social aspects towards embodied environmental impacts.

In the focus of the relevant technical category 18 different indicators, to name a few, from foundation-load bearing system, windows/doors in facades, balconies, roof, heating, air conditioning, fire protection and seismic behavior are identified.

In respect to the step of sustainable deconstruction the category of reuse (Components for re-use on site or offsite, materials for recycling, materials for recovery) and another one for waste disposal are established.

In respect to re-use, there is a reference to the Environmental Product Declaration (EPD), which contains information related to the product environmental performance obtained using life cycle assessment methodology (according to EN 15804, EN 15978). Results are expressed for a detailed list of indicators declared for each stage of the construction product from the sourcing/supply of raw materials to the end of life [8]. However, detailed indicators for Components for re-use on site or offsite are not provided.

The standard CEN/TR 17680 qualifies the sustainable construction process as step 3. It continues to impose, that the rebuild process is similar to a new building process. After step 4 (commissioning), consequently step 5 is proposed to represent "sustainable in use".

The diagram shows the representation of the demand profile versus the performance profile (Fig. 5).

The classification of indicators in performance and performance classes, from 0 to 3 provides a relation from class to performance and consequence. For example, if some technical indicator is qualified as class 3 (major or serious nonconformity), the description provides that "the building or part thereof has suffered or will imminently suffer total functional failure or need for immediate measures. Danger to life or health". The consequences are named as "catastrophic" (sic!) and action is needed.

The requirements for a successful implementation process are a unified taxonomy base in common standards. The use of the new proposed "Sustainability of construction works - Data quality for environmental assessment of products and construction work - Selection and use of data (Final draft) [9]", that will suspend CEN/TR 15941 is a very good example of this need for a common understanding and the harmonization of Life

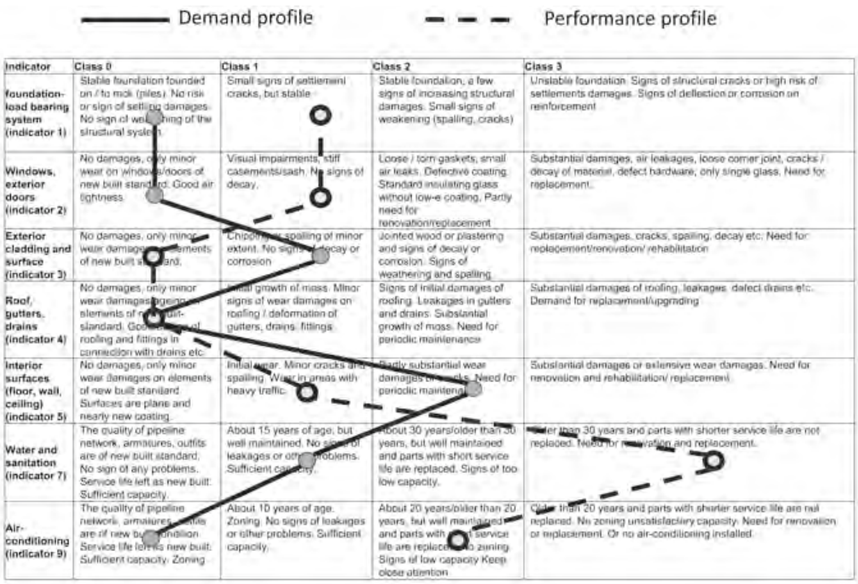

Fig. 5. Example of demand profile versus performance profile.

Cycle Modules to index elements in relation to their origin, distance to the site, storing capability and aspects of reusability.

A wider implementation of harmonized assessment methods is based in a common taxonomy.

Another regulation concerning aspects of material treatment is the standard for Dismantling of buildings as a standard method for demolition [10]. Relevant for the construction industry to become circular is the process of reuse of already used building material that comes from the end of life-cycle of objects in use. The remodelling and demolition process (ÖNORM B 3151) is to be organized in a structured way.

The waterfall model as of today contains 5 steps.

1. Avoid waste material by maximizing the re-use of buildings or building elements.
2. If there is no direct reuse possible, prepare usable building elements with cleaning and testing for their reuse and store them appropriately.
3. If the re-use is not possible, then the demolition elements and materials should be separated to their original destination material and brought into a recycling process such as glass -or wood recycling.
4. Only in the case of no appropriate recycling of the elements or material composites, a sustainable and also economic destination can be the deposition at a site, where there is a requirement for landfill or the waste material has enough thermal quality to burn the material, with the demand, that this measure is without any negative impact to air quality and similar.
5. Only if there is no possibility for any of the previous mentioned steps, there is the last option of putting the waste material under fully controlled conditions into a depot of waste material in an assigned area.

It is mandatory, for example in Austria since 2016, to have an investigation of pollutants and of impurities, a dismantling concept and an obligation to separate demolition waste.

4 Discussion

There is an identified gap between research and the creation of relevant regulations and also in relation to the dissemination of standards. This does cause a considerable risk in the usability of the standards and also in the adoption in the relevant market.

For example, in CEN/TR 17680, Sustainability of construction works the indicator for Air –conditioning (Indicator 9) is qualified Class 3 with the specification: "Older than 20 years and parts with shorter service life are not replaced. No zoning unsatisfactory capacity. Need for renovation or replacement. Or no air-conditioning in-stalled."

If this is taken literary, it can be read as absence of air conditioning will lead to a Class 3 qualification of a building, being "catastrophic" and replacement (of the whole building) is needed. This would, of course, impose quite a big impact on the European building stock, that are current without an air-condition.

Furthermore, there is the problem of decision process within the regulation committees.

The formulation and decision-making process of standards, in particular also in CEN/TR 17680. For example, in many national committees the decision-making is based on an electronic reply within 30 days to consent to a proposed regulation text. To consent or to sustain, only one single mouse click is necessary. In order to disagree, a full statement including various levels of explanation and improvements are required. So there is very often the case, that a new standard gets less than half of approvals (in relation to participating members), the majority abstained and no disagreement. This leads finally to a unanimous acceptance, since no vote was against it and the sustained votes do not count.

Standards are very important for the harmonization of rules. Furthermore, professionals have to respect the current state of the art in their executed work. In legal terms it means very often, to respect the standard (national or international on the topic). Whereas all legal documents have to be publicly available (such as legal databases with free access), there is no equivalent rule for national or international standards. The documents have to be purchased for quite a high price, with even no free access for judges in court or for research purpose. It is an industry of its own by the national standardization entity, although the members of committees do not receive any compensation or salary.

This is probably one reason for low involvement of universities and researchers sent to standardization committees. It does not increase the research budget of participating universities. On the contrary, it takes person-month, or least hours, from the research institution with no compensation. On the individual level of the researcher, the contributions do not count for publication and are anonymized.

On the other hand, relevant research initiatives start with a literature review. These searches do not include current (under development) or finalized national or international standards in most cases.

To prove this, testing of two search engines, Google Scholar and JSTOR, with the keyword 1: Sustainability of Construction Works and keyword 2: Indicators and keyword 3: standards did not bring up CEN/TR 17680, Sustainability of construction as a reference bibliography.

In respect to establishing a framework for sustainable refurbishment, standards can be a supporting element to harmonize terminology, taxonomy and general accepted principals and decision models (Fig. 6). However, the nature and methodology for application is very often not fully adequate and too generic to specific challenges and do not substitute real research tasks.

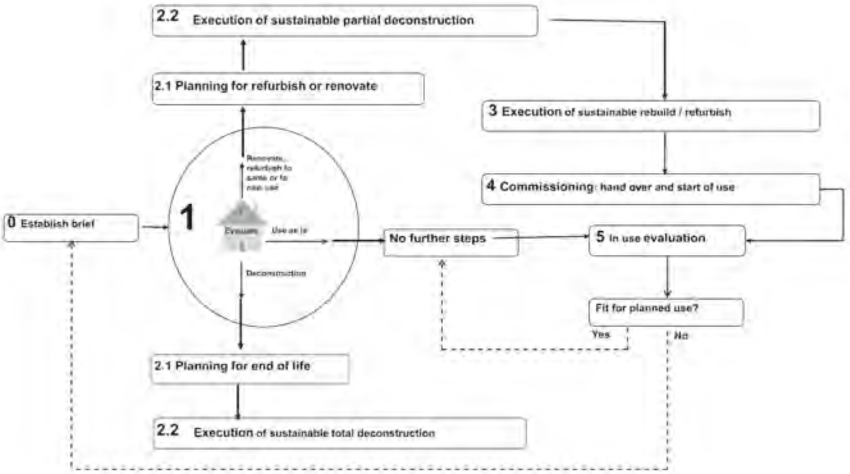

Fig. 6. Decision flowchart.

5 Conclusion

The task of sustainable refurbishment of existing buildings is one of the biggest challenges in the building sector in the next years. The requirements for a successful process are a unified process of refurbishment and taxonomy, together with a common understanding of an index of building-materials and elements in relation to their origin, distance to the site, storing capability and aspects of reusability.

By reviewing relevant regulations, their potential usability in respect to sustainable refurbishment was analysed and discussed.

However, some barriers were discovered, such as the weak link between research and the generation of standardization due to lack of compensation for research entities and universities, the formal decision process within the committees itself and the lack of a royalty free access towards these standards and regulations to be included in bibliography findings.

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Italian Regulations and Local Initiatives for Circular Economy in the Construction Sector

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Abstract. European Member States are required to promote initiatives and programs to shift their traditional linear economy into circular economy. The paper shows the Italian initiatives towards circular economy in the built environment, across different application level (national and local) and different drivers (top-down and bottom-up). The method of investigation regards an on-field research based on direct dialogue with various stakeholders of construction sector in the national context. The results show the current barriers to circular material flows and the successful initiatives in Italy. Firstly, the top-down strategies are reported, as well as existing standards, national regulations and local policy. Secondly, the bottom-up strategies are shown, stressing the local stakeholders involvement. Based on the discussion, potential improvements are highlighted to align the current Italian initiatives with the broader European Commission circular economy objectives, considering also the best practices developed in other European countries.

Keywords: Circular Economy · Policy Framework · Stakeholder Engagement · Reuse · Recycling · Design for Reversibility

1 Introduction

The construction sector is particularly relevant for achieving a circular transition, since it causes approximately 50% of all material extraction and 37.5% of total waste production, at European level [1]. Furthermore, it is responsible for 40% of primary energy demand in the EU and 36% of greenhouse gas emissions [2].

Circular economy, declared as a priority in the context of European policy [3], aims at a sustainable economic system and a resource efficiency by preserving the added value of products as long as possible. The circular economy objectives, highlight the relevance of waste management, underlining the implementation of the waste hierarchy (prevention, reuse, recycling, energy recovery and, lastly, landfill), already defined by the Waste Framework Directive 2008/98/EC.

Circular economy has been re-proposed by the European action plan [4], underlines the importance of strategies oriented towards the re-design of products and processes, based on sustainable consumption models.

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The transition towards circular economy, recently, is even more important as it is part of the six environmental objectives of the Taxonomy [5], which allows the definition of sustainable activities (avoiding greenwashing), relating to every economic sector including, therefore, construction.

Currently, the topic promoted by European policy most discussed in literature is related to the improvements in circular management of inflow and outflow materials from the building process, improving waste identification and quality processing, flow management and planning during the construction phase and the end of life [6]. Other studies propose the reuse strategy as the best practice of building materials management [7]. Further studies are focused on the quantification and mapping of secondary materials stored in products, buildings and infrastructures, for the geolocation of reusable and recyclable urban material resources [8].

Another important topic is related to the change in design process to circularity. Reversibility, adaptability, flexibility, and design for disassembly are the main strategies to extend products and buildings' useful life [9]. Construction technologies, as well as modular elements, dry technologies, mechanical connections, off-site constructions, are relevant enablers to achieve a circular design process. Several studies agree with the importance of Building Information Modeling (BIM) to monitor the use of resources during the whole life cycle, sharing information between operators and simulating building and components reuse scenarios [10].

Nevertheless, in practice, circular economy strategies are rarely applied at the building level in a systemic manner and in a life cycle perspective. Moreover, there is still different and fragmented circular strategies application in the European countries, highlighting the need for more effective and coordinated actions and policies promoted by European Commission [11].

In this paper the circular economy application in the Italian context is presented in depth, showing the top-down and bottom-up initiatives in the Italian context, both at national and at local level. The scope of paper is to give an in-depth investigation, useful for policymakers, on the Italian level of alignment to the European target on circular economy, highlighting barriers and opportunities for improvement.

2 Method of Investigation

The results come from an on-field research based on direct dialogue and semi-structured interviews with various stakeholders of construction sector at national scale, favoring the medium-large sized companies: policymakers, manufacturers, designers, investors, constructors, facility managers and waste managers. The sampling procedure is based on a "reasoned" selection of stakeholders, which concerns operators with experience within circular strategies. This allowed to proceed with the identification of the expected results, concerning the current barriers for material circularity and the best successful initiatives at national and local Italian context.

3 Current Barriers to Circular Material Flows in Italian Context

Statistics show that in Italy 76% of waste from demolition and construction (excluding excavated earth) is recycled or recovered, therefore the objective established by the Waste Framework Directive (WFD) (Directive 2008/98/EC) is achieved [12]. However, the largest quantity of construction and demolition waste (CDW) in Italy is made up of inert materials, which represent 75–85% of the total CDW [13]. The percentage of the WFD is consequently satisfied only by the treatment of the aggregates, not considering other lighter fractions of construction and demolition waste, such as materials of synthetic origin, which may have a higher potential for reuse and recycling. Furthermore, the WFD only requires sending for recovery, and this does not always lead to effective recycling. In particular, recycled aggregates are used for road foundations and fillings, therefore downcycled.

To overcome this situation towards more effective circularity, the analysis conducted across Italian practitioners shows economic, logistical and cultural barriers currently existing in Italy.

Italy has a large territorial surface and a lot of natural resources available for the production of building materials, such as aggregates for the production of concrete, clay for the production of bricks, etc. which constitute the majority quantity of construction material. Therefore, in Italy, resource extraction is relatively cheap, and on the economic point of view, stakeholders are not incentivized to find a more sustainable resource utilization and management through recycling and reuse.

Moreover, Italy does not have restrictive regulations or tax on extraction of raw materials, hence the use of raw materials is sometimes more economically advantageous than the use of secondary ones.

The lack of market demand for recycled materials caused long periods in storage centers of resources. In fact, sometimes, recycling plants earn more from the collection of inert waste rather than from the sale of secondary raw materials.

On the other side, in Italy there are not restrictive landfill ban, resulting in lower landfill fees. The landfill price can vary by region (law 549/1995 on solid waste landfill costs) and sometimes it can be comparable or more advantageous to the gate fee of recycling plant. Consequently, there is a lack of interest in improving the quality of demolition waste, to prefer reuse or recycling rather than landfill. This is also caused by the lack of pre-demolition monitoring which could stimulate greater waste differentiation.

Logistical barriers represent a further obstacle for recycling practices: transport distances lead to neutralizing the economic and environmental advantages. For a small quantity of waste, generated in medium or small demolition works, a long distance from the treatment plant can lead to prefer landfill, if it is closer.

In terms of design process, through discussion with stakeholders, it also emerged that in cases of building refurbishment or demolition and new construction, the need to reduce process times leads to an overlap of building operation, e.g. demolition practices at the same time of refurbishment executive design. Consequently, the materials emerging from the demolition process (e.g. false ceilings, floors, bathroom fixtures, etc.) do not find a destination within the refurbishment intervention (as they have already been disposed before the drafting of the definitive and executive project), thus resulting in the generation of waste related to products often still in good condition. Moreover, the traditional

Italian constructive techniques (load-bearing structure in reinforced concrete, brick-cement floors and brick walls with plaster finish), do not facilitate the separation of valuable materials potentially reusable.

4 Successful Top-Down Initiatives at National and Local Italian Level

Top-down initiatives include actions and policies activated at the highest level, such as by government or Public Administrators. The national legislation is fundamental for influencing the practices towards circularity, for example encouraging the market of secondary materials, facilitating the waste management and circular building process.

From a circular point of view, it is decisive to consider the materials coming out from construction processes no longer as waste but as resources, introducing regulation related to the 'End of Waste' (EoW). The 'EU Construction and Demolition Waste Management Protocol' [14] highlights the particular commitment within national policies aimed at defining EoW decrees.

In recent years, Italy has worked on the definition of the EoW criteria for inert construction and demolition waste (Decree 152/2022). The EoW decree defines the recovery process of construction and demolition waste and the transformation process to be able to classify it as a new product. In Annex 2, the technical standards for the use of recycled aggregate considers not only the use for construction of civil engineering earthworks, road, railway and airport foundations, but also the use to produce new concrete (harmonized with UNI EN 12620).

However, this Italian EoW decree only concerns inert waste. There are still not reference legislation related to other types of products and materials. Moreover, the need for coordination and harmonization of EoW policies among Member State is still under discussion.

An important initiative to encourage the reduction of raw materials consumption and landfill in Italy is represented by Green Public Procurement (GPP) (Legislative Decree 50/2016), according to which Public Administrations must integrate Minimum Environmental Criteria (CAM) in the field of public tenders. CAM (approved with Ministerial Decree 256/2022) requires several sustainability strategies across the building process (design, construction, maintenance, end of life) and some strategies fully achieve the circular economy objectives.

There are mandatory requirements about minimum percentage of recycling content in building products (e.g. concrete, steel, bricks, each type of insulating material, etc.) and about disassembly of construction parts.

The percentage value of the recycled material content must be demonstrated through a certificate in which this information is clearly reported, for example Type III environmental product declaration (EPD), 'ReMade in Italy' certification and other certified label.

Moreover, a particular CAM requirement is related to the disassembly and end of life: at least 70% (by weight) of the building components, excluding systems, must be disassembled at the end of their life to then be subjected to preparation for reuse, recycling or other recovery operations. The designer must declare the 'plan for disassembly and selective demolition', based on the ISO 20887 standard 'Sustainability in buildings and civil engineering works – Design for disassembly and adaptability – Principles, requirements and guidance', or UNI/PdR 75 'Selective deconstruction – Methodology for selective deconstruction and waste recovery from a circular economy perspective' or on the basis of any information on the disassembly of one or more components, provided by the EPDs compliant with UNI EN 15804.

In the context of public building, another successful Italian top-down initiative regards the use of BIM during the design phase. BIM enables efficient information sharing throughout the supply chain, reducing the risk of building design errors and waste during the construction phase [15].

In compliance with the Italian Ministerial Decree 560/2017, in public works, the use of BIM digital tools is mandatory, in order to allow the interoperability and usability of building project information by each operator during the design, construction and management process. The mandatory use of BIM concerns projects that exceed a cost limit. This cost limit decreases every year and by 2025 it will affect most of the public projects.

Locally top-down initiatives are less frequent. A local successful initiative is the 'Lombardy Roadmap for Research and Innovation on Circular Economy', developed in 2019, that intends to provide a framework for the development of a circular economy transition in the Lombardy Region, with the aim to stimulate the cooperation between public and private stakeholders and build strategic initiatives on circular economy. The document provides detailed descriptions of the strategic research and innovation priorities to the related phase of circular economy value chain. Hence, the structure is organized across production/design, distribution, use/service maintenance, collection, remanufacturing/repair, recycling and feedstock.

The 'Lombardy Roadmap' introduced circular economy as one of the main drivers to foster the development of emerging industries in the Region. Strategies to boost circular economy in the Region were set starting from the needs and the priorities collaboratively pointed out by diverse regional stakeholders.

5 Successful Bottom-Up Initiatives in Italian Context

Bottom-up initiatives refers to the strategies derived from stakeholders' activities, defined by groups of operators, such as investors, manufacturers, designers, etc.

For example, the voluntary initiatives to obtain building sustainability certification (e.g., a green building rating systems) influence the building process towards circularity and sustainability, with added value in terms of increasing building economic value, lowering maintenance costs, and enhancing wellbeing and visibility for occupants.

In Italy, the use of Green Building Ratings Systems (e.g. LEED, CasaClima) is often encouraged by the fact that in some urban context sustainability certification increases the commercial value of the building. This objective, which is increasingly requested by investors, influences the choices of intervention and practices along the process, determining compliance with the sustainability and circularity criteria to be achieved in order to obtain certification.

The choice to respect criteria of a sustainability protocol (in Italy the most used are LEED and BREEAM), influences the decisions and behaviors of operators. For example, the management of waste and the traceability to recycling are supervised by the LEED Accredited Professional (LEED AP). The building sustainability certification encourages, also, the use of LCA as a tool to demonstrate the actual environmental impacts avoided by materials and construction solutions.

In general, the building sustainability certification reward mechanisms favor the development of circular practices not yet commonly applied and helps to optimize the material use and to lower costs for all the stakeholders.

Included in the bottom-up initiatives are the voluntary adhesion to organized working groups or focus group among the stakeholders of the building value chain, to set a virtual place useful to share knowledge and experiences on circular economy. The goal is to collect, develop and disseminate circularity procedures in the construction sector and best practices, providing information on current standards and figure out future development advisable to government.

In this context, in 2017, the European Commission and the European Economic and Social Committee (EESC) created the European Circular Economy Stakeholder Platform (ECESP), a European platform that would activate networks between stakeholders at local, regional and national levels, for the exchange of ideas and information.

At Italian national level, ICESP (Italian Circular Economy Stakeholder Platform) has been configured as ECESP 'spin-off' to collect initiatives, experiences and critical issues on the circular economy in Italy, and then communicate them to the ECSP European network. ICESP working groups favor dialogue and synergies between institutions, central and local public administration (which make up 8.7% of the total participants), citizens and third sector (which representing 10.4%), training and educational sector, research and innovation (18.1%) and trade companies and associations, which constitute the predominant reality within the ICESP network (62.8% of the total participants). The working group give useful output (surveys, report, position papers, etc.), aimed at encouraging top-down initiatives by policy makers [16]. In Italy, another active working group on circular economy is related to the bottom-up initiative of Green Building Council Italia. This working group is composed by designers, constructors, manufacturers, investors, universities, building sustainability experts, etc. For example, an output is a position paper that identifies 13 key actions for the transition to the circular economy in construction sector specific for Italy [17].

6 Discussion

Against the obstacles that persist in Italy to improve the circularity of material flows, the previous paragraphs show that there are also several successful initiatives to overcome the barriers.

However, the circular transition is still slowing down, and the reason is probably due to the fact that the incentives do not concern all types of building materials (the EoW concerns only aggregates) and not all types of buildings (the CAM applies only to public buildings). Furthermore, local initiatives are fewer and not equally distributed throughout Italy.

The lack of specific restrictive regulations (e.g. for landfills and resource extraction) causes less awareness among stakeholders who have not understood the actual (economic) benefit of the commitments required by top-down initiatives.

In fact, exploring some European examples, countries which statistically show a higher rate of waste recovery (i.e. avoiding landfill) have waste regulations (even also prior to the WFD). For example, Germany has introduced the 'Kreislaufwirtschaft Bau' (Circular Economy in Construction) initiative since 1995, as a voluntary commitment to reduce the quantities of construction and demolition waste sent to landfill, which has led to high waste recovery rates. Belgium, Netherlands, United Kingdom and Denmark, have legislation establishes specific bans or taxes to increase the fees of landfills. The high cost of landfill tax encourages stakeholders to prefer other types of waste destinations, and practices of reuse and recycling is more frequent.

Belgium and the Netherlands have a different contextual characteristic from Italy, in fact the scarcity of raw materials favor the recycling of existing materials. Instead, United Kingdom presents, as well as Italy, a territory with huge quantity of inert raw materials: hence, to promote secondary materials economically advantageous, United Kingdom imposes an Aggregates Levy.

In Italy, while recycling (mainly downcycling) reaches the statistical recovery rate of 76%, instead the practice of reuse is still poorly applied in practice (as happen in other European countries). Reuse is still poorly applied in practice because there are still several barriers. The analysis of the stakeholders' perspectives highlights the lack of legislation related to the tests, quality, performance and technical process necessary to certify the reused materials (without certification the materials are not used for liability reasons).

Stakeholders also highlighted challenges from technological aspects: current constructive systems are not designed for disassembly; therefore, it is difficult not to damage the elements during disassembly. Disassembly is also more expensive than demolition due to the use of manpower. Moreover, logistic system for reused materials has not yet been developed.

To achieve more efficient end-of-life material flows towards reuse, traceability system is needed to monitor all material/waste fractions and cover the entire process, also considering the possibility of avoiding waste through the extension of the life cycle of the building parts (not only when demolition has already been decided).

It is essential to define, at the Italian level, a system for the traceability of building and demolition waste, also through the introduction of pre-demolition audit tools. It is then essential to improve the traceability of the components of the building in order to map its "history" and its use, and therefore promote its reuse.

The introduction of the material passport [18] could be a solution for increasing knowledge about the materials stored inside the building, raising the chances of reuse and recovery.

In fact, materials passport maintains knowledge of all building materials in the long term, preserving their (economic) value. Material passport systems and databases can interact with BIM software and can be available to all users involved. Through a shared material passport system, it is also possible to know the quantity and the location of materials stocked in the urban mining. Nevertheless, legislation on mandatory use of material passports has not yet been introduced in Italy, and a common definition and harmonized tools/systems are lacking [19].

Moreover, it is necessary to encourage a building process that create relationships among stakeholders (in particular designers, constructors, manufacturers, and demolishers) in order to share knowledge and information to improve the change in design process towards circularity. If in Italy BIM is quite diffuse and incentivized by legislation, and the disassemblability of construction is required by CAM, there is not yet a wide choice among reversible construction solutions.

In fact, most of the time, the reuse of products is hindered by the impossibility of obtaining materials that are still in good condition following demolition activities (due to demolition practices that damage the products).

From a sustainability point of view, circular strategies could only apparently bring environmental benefits in a single life cycle phase. It is possible that circular strategies shift environmental impacts to other life cycle phases. For example, promotion of recycling considers the environmental benefit of avoiding landfill disposal, but without considering the environmental implication of the recycling process activities (transport, reprocessing, etc.). Hence within the promoting initiatives towards circular economy, it is necessary to emphasize improvements towards sustainability (not only circularity) combining the use of tools based on Life Cycle Assessment methodology in order to evaluate the most environmentally sustainable solutions, both for material construction solutions and for building end-of-life management.

It is therefore necessary to promote the use of Life Cycle Assessment (LCA) in upstream, during the decision-making process, to improve a planning process for waste prevention, and in downstream, during the phase of waste management and the end-of-life process. Consequently, it is important to develop supporting tools easily usable by operators or introduce professional support figures prepared for the use of more inclusive tools.

7 Conclusion

The paper shows that Italy still presents various barriers for the activation of circularity and material efficiency processes, also related to the fragmented and discontinuous relationships of the operators in the sector.

Some policy recommendations to promote circular economy in the construction sector, at Italian level, are summarized below:

- the improvement of traceability of materials/waste, through the development of traceability systems, which act on national context, but which are harmonized with initiatives at European level;
- the management of construction waste and demolition waste separately, in relation to their different reuse/recycling potential;
- the establishment of a maximum percentage of construction waste allowed on site, encouraging the collection and reuse chain of construction site scraps and waste;
- the definition of End of Waste criteria for all types of waste materials;
- the establishment of a taxation on raw materials and on the disposal of waste to landfill: this in order to reduce the extraction of raw materials (for example by prohibiting the opening of new quarries) and to encourage the reuse and recycling of products;

– within the GPP, the definition of rewarding criteria relating to ambitious percentages of reuse and reusability rate of the building products;
– within the GPP, the introduction of LCA requirements, supporting the operators by trainings and methodological standards.

To achieve circular economy in the built environment, initiative at national and local level is important as well as the international coordination and harmonization in terms of policies, practices and enabling tools. Moreover, the promotion of cooperation between stakeholders of the building value-chain is priority to allow co-creation of techniques and the diffusion of knowledge and awareness of circular strategies among stakeholders. Future improvements should concern the fields of new circular business models within win-win solutions, based on services, support tool for environmental assessment, and training program towards new skills and competence to enable circular building process.

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Framework for a Multi-level Approach for Testing the Construction Demolition Waste Hierarchy

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Abstract. The Waste Framework Directive (WFD) proposes a Waste Hierarchy (WH), a list of waste management strategies ordered from the most to the least preferable and often illustrated as an inverted pyramid. Waste prevention is at the top of this pyramid, followed by preparing for reuse, recycling, and then other recovery activities such as waste to energy. At the bottom of this hierarchy, the waste management strategy to be avoided is waste disposal at landfills.

Although this hierarchy establishes a logical framework for waste management policies, case-by-case assessment shows many exceptions to the rules implicit in this structure. Indeed, depending on the materials and constructive solutions, the order proposed by the WFD can be modified by considering a detailed LCA. On the other hand, when performed on an element level, the results of LCA may not be viable to inform policymakers on the best course of action towards a more sustainable built environment. This paper proposes a multi-level approach – at a material, element and building level – combining the waste hierarchy with the 9R framework. Assessments of building refurbishment at the building or element level can yield vastly different results, which may be relevant when addressing questions posed by each type of stakeholder according to their scope of action.

Keywords: Construction and Demolition Waste Management · Construction · Life Cycle Assessment (LCA) · Refurbishment and Maintenance · Waste Hierarchy (WH) · 9R Framework

1 Introduction

A circular economy (CE) is restorative and regenerative by design and aims to keep products, components and materials at their highest utility and value at all times [1]. A CE approach helps to reduce environmental degradation and fosters resource efficiency. Ultimately, it minimises waste generation, thus enhancing sustainability [2]. Sustainability assessment is a field in continuous evolution in which the legal framework is crucial to push the adoption of sustainable principles. However, it is important to note that there is a disparity between legislation evolution and the ongoing scientific development and

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methodological approaches. This paper proposes a combination between the 9R framework (9R) [3] as a frequently used hierarchy and the Waste Hierarchy (WH), proposed by the Waste Framework Direct (WFD) [4], and its adaptation to the construction sector. Additionally, a framework is explored to guide various stakeholders' decisions, using an approach focusing on the end-of-life (EoL) phase and based on currently available LCA data. A more comprehensive LCA approach is difficult to achieve due to the complexity of LCA studies and lack of research focusing on alternative EoL scenarios. This work responds to the research gap in the application of the WH and 9R to the construction sector by introducing a framework to guide decisions for refurbishment and maintenance purposes.

2 Literature Review

2.1 The Waste Hierarchy

The WFD [4] was initially published in 1975 and was revised in 1991, with the most recent version published in 2008. Since then, several authors proposed adaptations tailored to specific sectors, such as the Delft Ladder (2000) developed for application in the construction sector. This ladder recommends that, for optimal construction practices, the use of "*hard-to-recycle materials*" should be minimised and the separation of materials and building elements enhanced, stating that constructions should be designed for easy disassembly [5].

Table 1 contains the definitions of recycling and reuse from different sources, highlighting similitudes and differences among proposed definitions. The definitions in most of the documents presented [6–9] are in accordance with the WFD [4], however, the other documents define reuse acknowledging different purposes than the one for which it was initially conceived [10, 11]. The WFD was amended in 2018, but the definitions remain unaltered, and '*reuse*' only encompasses the cases in which the product/component serves the same purpose for which they were conceived. The WFD also defines '*preparing for reuse*' differentiating it from '*reuse*'. In the context of '*reuse*', the material or object has not yet become waste. On the other hand, in the case of '*preparing for reuse*', the material has already been designated as waste, and to be declassified as waste, specific actions such as checking, cleaning, or repairing are needed. These recovery operations ensure that products or components are prepared for reuse without requiring any additional pre-processing. The Ellen MacArthur Foundation definition of '*reuse*' [12], which intends an international scope, seems to be partially in accordance with the WFD but seems to include '*preparing for reuse*'. Other definitions, such as repair, need to be further detailed in the waste hierarchy.

Several concerns within the WH were pointed out in the literature, such as: *"not distinguishing between different forms of recycling"* and even though it presents a *"solid strategy for avoiding landfill, there is doubt about the merits of the hierarchy concerning minimising environmental impacts and natural resource use*". Some of these issues can be overcome by providing stricter guidance on WH implementation [13].

Table 1. Review and comparison of reuse and recycling definitions.

[Year] Reference	Reuse definition	Recycling definition
[2008] Directive 2008/98/EC 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance) [4]	Any operation by which products or components that are not waste are used again for the same purpose for which they were conceived	Any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations
[2016] Protocolo de Gestão de Resíduos de Construção e Demolição da EU [6]	*The definition coincides with the Directive 2008/98/EC* [4]	*The definition coincides with the Directive 2008/98/EC* [4]
[2018] Guidelines for the waste audits before demolition and renovation works of buildings [10]	Using materials or building elements on more than one occasion, either for the same or for a different purpose, without the need for reprocessing	A process where materials are collected, processed and re-manufactured into new products or use as a raw material substitute
[2020] CE Principles for Building Design (EU) [7]	*The definition coincides with the Directive 2008/98/EC* [4]	*The definition coincides with the Directive 2008/98/EC* [4]
[2020] ISO 20887:2020 Sustainability in buildings and civil engineering works [11]	Use of products or components more than once for the same or other purposes without reprocessing	Ability of component parts, materials or both to be separated and reprocessed from products and systems and subsequently used as material input for the same or different use or function*
[2020] Regime Geral de Gestão de Resíduos (RGGR) [8]	*The definition coincides with the Directive 2008/98/EC* [4]	*The definition coincides with the Directive 2008/98/EC* [4]

(*continued*)

Table 1. (*continued*)

[Year] Reference	Reuse definition	Recycling definition
[2021] Framework Level(S) [9]	*The definition coincides with the Directive 2008/98/EC* [4]	*The definition coincides with the Directive 2008/98/EC* [4]
[2021] Ellen MacArthur Foundation Glossary [12]	The repeated use of a product or component for its intended purpose without significant modification. Small adjustments and cleaning of the component or product may be necessary to prepare for the next use	Transform a product or component into its basic materials or substances and reprocess them into new materials**. Embedded energy and value are lost in the process. In a circular economy, recycling is the last resort action

*definition of recyclability
** definition of recycle

2.2 The 9R Framework

Parallelly to the WH, the 9R proposed by Potting also defines one hierarchy to reduce environmental impacts and boost the circular economy from the most preferable approach: refuse; to the least preferable one: recover [14].

Previously to the 9R framework, a wide variety of n-R approaches was found in literature varying not only the numbers of Rs (3Rs, 4Rs or 6Rs), but also assigning different attributes and meanings to each R. Notably, the number of Rs tends to increase in recent contributions, published after 2010 [15].

Potting recognises exceptions for his framework and advises that the examination of rebound or secondary effects is advisable, but, in general, increased circularity in a product chain results in reduced consumption of natural resources and materials. This, in turn, leads to fewer environmental effects within that product chain and related chains. Although the hierarchy ranks the most to the least favourable strategy, there is still a great need to consider the best solution approach applicable to each case within each specific context [16].

2.3 Life Cycle Assessment Approach

LCA studies are one methodological approach to assess the impacts associated with each activity, product, or material. LCA studies should have a holistic approach, focusing on all the stages of the life cycle of a product, including the EoL. Therefore, LCA could be used to determine the best course EoL strategy, if not for their complexity and time-consuming nature [13].

Neither of the hierarchies that were previously presented, WH and 9R, consider the different characteristics of the different materials. For example, steel structures with demountable connections and prefabricated assemblies comprise mostly reusable materials, while concrete structures may generate recyclable materials [17]. Because different materials require different EoL strategies, sorting is considered a preliminary and essential step before the appropriate waste treatment [18]. Separation allows for action on a smaller level, allowing the preparation for reuse to reduce material consumption or adopting a more appropriate EoL strategy based on the specific material.

LCA studies results, focusing on EoL strategies, would be an important data source but, unfortunately, are hard to compare for various reasons: i) lack of transparency in the definition of the system boundary, ii) uncertainty about life cycle inventory (LCI) data origin; or iii) sensitivity analysis of the assumptions made [19, 20]. Adding to this complexity, different locations have differences in climate, energy mix or the local market available, meaning the same product will have incomparable results [21].

The paper aims to combine the two hierarchies, WH and 9R, adapt them to the construction sector, and create a guideline to help stakeholders choose the preferable EoL strategy.

3 Methodology

3.1 Combination of the 9R Framework and Waste Hierarchy

As previously stated, the WH's main goal is the generation of less waste, not necessarily the minimisation of environmental impacts. As for the 9R, it presents exceptions in the form of rebound or secondary effects. The main proposition of this paper is the association of the two frameworks, as presented in the WH and 9R [3, 22–24], Fig. 1, and their application to the construction sector, presenting some practical examples in Table 2.

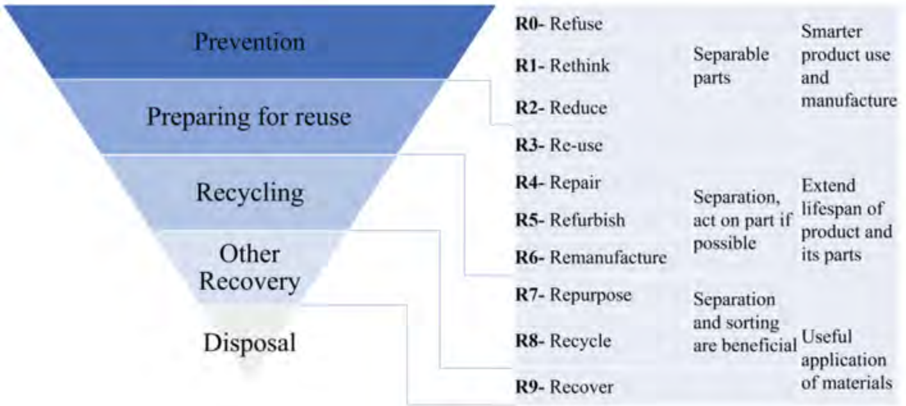

Fig. 1. The WH and 9R [3, 22–24].

Table 2. The 9R Framework, definitions, and examples.

9R	Definition	Example in construction	CE approach
R0-Refuse	Avoid both virgin and processed materials, no action	Acceptance of damage (e.g., the darkening of a natural stone with no substitution needed)	Smarter product use and manufacture
R1-Rethink	Design or redesign a product or component based on sustainability and circularity principles, choosing a more sustainable option, Solving with minimal resources	Design for disassembly (e.g., Modular construction, demountable building elements)	
R2-Reduce	Reduce the use of raw and processed virgin materials, increase efficiency, and choose the most sustainable option	More precise design and construction (e.g., BIM use of clash detection)	
R3-Reuse	Reusing products, components, or virgin materials (whether they have previously been refurbished), preferably reusing in the same place, avoiding transportation	Reuse elements from previous construction (e.g., use of a marketplace. Note: If possible, avoid transportation)	Extend the lifespan of the product and its parts
R4-Repair	Regular maintenance and repair, whether (or not) combined with redesign and digitalisation. Minor adjustments, minimal intervention	Maintenance (e.g., BIM 7D for Facility Management throughout the building's life cycle)	
R5-Refurbish	Restore products and parts such that they are "like new"	Refurbish elements of the construction (e.g., wooden floor tiles.)	

(*continued*)

Table 2. (*continued*)

9R	Definition	Example in construction	CE approach
R6-Remanufacture	Making the same new products or parts from previously made products and/or parts	Remanufacture elements from previous construction (e.g., using bricks that were previously deconstructed)	
R7-Repurpose	Reusing products and/or parts but with different purposes, whether combined with refurbished	Repurpose elements from previous construction (e.g., using an old door for the top of a table)	
R8-Recycle	Conversion of products and parts to virgin materials and reuse	Recycling materials for avoidance of virgin ones (e.g. plywood)	Useful application of materials
R9-Recover	Energy recovery from materials (also called thermal upcycling),	Recover elements from previous construction (e.g., Construction and demolition waste mass as volume, material incineration)	

3.2 Framework

A building is very different from a usual industrial product, as it contains many different components, made with different materials, with different impacts.

Circular construction supports easy component separation and accessibility, enabling substitutions throughout a structure's lifetime. However, much of the built environment does not align with these principles. In addition, neglecting minor damages, like infiltrations, can result in significant issues if left untreated. Opting to refuse may lead to greater impacts over time, challenging the effectiveness of established hierarchies.

In light of the specified requirements of the construction sector, the Framework for refurbishment and maintenance in Fig. 2, introduces a proposed framework aiming to implement the Waste Hierarchy (WH) and the 9Rs (Reduce, Reuse, Recycle, etc.) in the construction industry, with the primary objective of minimising environmental impacts. This framework offers stakeholders decision support for refurbishing and maintenance of existing buildings. It is based on the Delft ladder [5], but Circular Economy goals are added to waste reduction targets. It includes a multi-level approach considering the building, component, and material level. This framework is yet limited at the material level due to a lack of results from comparative LCA studies assessing different EoL strategies for each material.

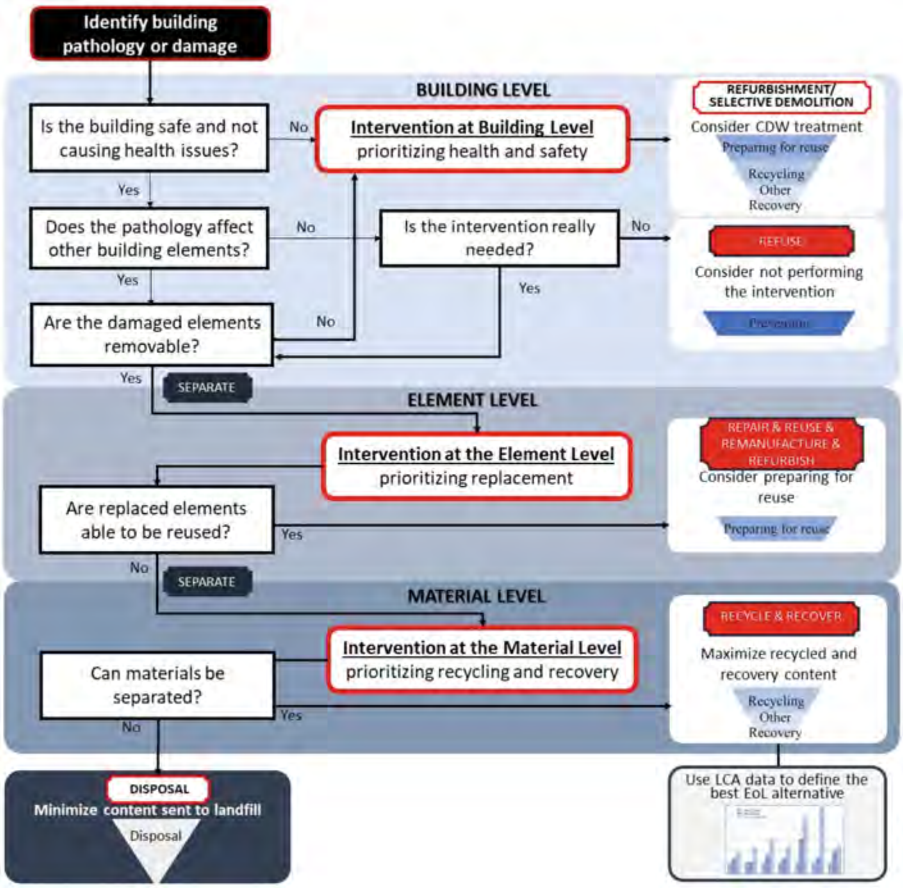

Fig. 2. Framework for refurbishment and maintenance.

4 Discussion

Compared to most other sectors, the construction industry is unique, particularly due to the extensive consumption of resources, the use of different materials, and the prolonged lifespan of buildings. As a result, managing maintenance activities and end-of-life processes within the built environment poses unique challenges.

The association between WFD and 9R, presented in Fig. 1 was previously proposed by Zhang [23]. However, according to the definitions provided by the WFD (a European regulation applied within this geographical boundary), repurposing would be more adequate within recycling due to the change of original purpose. The definitions of the European Union are vague, mainly focusing on waste reduction, raising some concerns about its effective minimisation of environmental impacts. This combination between WH and 9R is suggested to further define and detail the WFD and adapt it to the construction sector, with practical examples.

The proposed framework in Fig. 2, addresses the second goal of this paper, defining a decision framework to guide stakeholders throughout refurbishment and maintenance. LCA results and generic data play a very important role within this framework, better informing about the preferable EoL strategy for each material. However, not all LCAs results meet the requirements because of a general lack of transparency in defining system boundaries, undisclosed origin of inventory data, and absence of sensitivity analysis of assumptions, making them impossible to compare [19]. Another important aspect of LCA results is that they usually cannot be compared due to the assumptions and choices made about the EoL of a product or material. This means that within a certain product's LCA, an EoL strategy, such as recycling, will be considered, but not an alternative EoL strategy, such as reuse or incineration. This absence of comparisons creates uncertainty about the impacts of alternatives, lacking clear guidance on the best EoL strategy for each material, backed by statistical data.

5 Conclusion

Due to the complexity inherent to LCA studies, the WH and 9R seem to be the streamlined approaches to inform decision-makers about the preferable approach aligned with CE principles. Nevertheless, neither approach considers the differences in the impacts of different materials. For that reason, a new framework was proposed to support stakeholders in deciding refurbishing or maintenance alternatives on multiple levels: at the building, component, and material. Four main conclusions can be drawn together:

- The WHD does not discriminate the different types of action contained within, indicating that it might need a new update.
- Separation (of components and materials) should always be considered to enhance the reuse of components and recycling of materials.
- Interventions in the built environment should be preventive and strictly necessary, extending the life cycle of the components and of the building, minimising the need for new materials, and reducing impacts.

Finally, it is important to highlight that comparative LCA at a building scale seems to be difficult, but at the material scale, the assessment could inform about the preferable strategy at the EoL. This paper identifies the need for comparative studies focusing on the EoL of the different materials to support deviation from the WH and inform what the best EoL strategies for each material are.

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End-of-Life as a New Beginning: Pre-demolition Audits, Digital Platforms and Skilled Labour as Enablers of Circular Economy

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Abstract. One of the main issues with applying Circular Economy (CE) principles to the construction sector sits at the End-of-Life (EoL) of buildings. How to recover the materials and then how to reintroduce them into the economy are fundamental problems that lack immediate solutions. The status quo in the EoL of buildings has always been demolition followed by deposition at a landfill (linear economy), thus, to change this approach, there is the need to replace demolition with deconstruction. This causes new problems, as buildings vary greatly, there is a need for pre-demolition audits, that can report on the recoverable materials, potential generated waste and plan the deconstruction intervention. Here, new problems arise, such as the lack of methodologies to intervene or skilled labour that makes deconstruction possible. However, at that point, even when materials are recovered there is the problem of how to reintroduce those materials back into the market. Here, digital platforms can bridge that gap, making it possible for the recovered materials to be posted in a marketplace where the designers of new buildings (or building renovations) can access the circular materials available to introduce into their designs. Thus, this paper aims to present a possible solution to the problem of introducing CE into the built environment, proposing pre-demolition audits, digital platforms, and labour upskilling as enablers for a greener future.

Keywords: Circular Economy · Pre-Demolition Audits · Digitalization · Deconstruction

1 Introduction

The construction sector is one of the main contributors, worldwide and, specifically in Europe, to economic growth [1]. However, that growth is still heavily driven by a linear economy, with high consumption of virgin natural resources, where the construction sector is responsible for about 50% of all extracted materials, and about 35% of all waste sent to landfills [2], with materials such as cement and steel, central to the sector, responsible for 14% (about 7% each) of all man-made emissions [3]. Thus, applying circular economy (CE) to the sector, by recovering materials from end-of-life (EoL) buildings, and reapplying them to new construction, the two issues can be tackled: depletion of resources and waste production.

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However, the construction sector is unique in the sense that buildings are prototypes; systems and solutions are shared, but the design and onsite construction varies greatly. Also, most buildings have been designed with preoccupations on their construction and maintenance phases disregarding the EoL. The lack of preparation for the EoL makes this stage one of the main hurdles for applying CE principles to the built environment: how to deconstruct unprepared buildings [4].

New methodologies such as *Design for Disassembly* (DfD) [5] and the proliferation of modular construction will, eventually, change this paradigm [6]. However, today, about 85% of all buildings in the European Union (EU) have been built before 2001 and it's expected that, in 2050, between 85% to 95% of the buildings built today will still be in use [7]. As buildings are responsible for about 40% of energy consumption in the EU, one of the targets of the *European Green Deal* is that, by 2050, every building should be a *Zero-Energy Building* (ZEB) including already built buildings [8], thus, most buildings will need significant interventions in their lifecycle.

2 Methodology

This paper has the main target of exploring how pre-demolition audits, digital platforms and the upskilling of the labour force in the construction sector can, together, bring the circular economy to a widespread application. It is organised by presenting, in the results section, a description of the considered enablers, the main barriers, how those barriers can be surpassed and how each enabler contributes to the adoption of CE as a whole. The results section ends with a vision of how all enablers work together and how CE can be applied to EoL buildings and connected to the design phase.

The work was developed by documental research to identify CE, pre-demolition audits, digital platforms or marketplaces and skilled labour. The aim was to be able to properly define these subjects and link them to their potential role in enabling CE in the construction sector.

The data and information collection took place on *ScienceDirect*, *Scopus*, and *Google Scholar* using the following keywords (isolated, combined, synonyms and acronyms): *"Circular Economy", "deconstruction", "demolition", "construction sector", "audit", "pre-demolition", "digital platform", "marketplace", "construction demolition waste", "sustainable", "barrier", "opportunity", "labour", "upskilling", "new professions", "LIDAR", "photogrammetry", "radar detection", "drone", "automatization", "BIM", "scan-to-BIM", "point cloud",* and *"model"*. Other sources, namely institutional were also consulted: *European Commission Environment* [9], *EUR-Lex* [10], and *EEA Grants Portugal Environment* [11].

3 Results and Discussion

3.1 Pre-demolition Audits

Deconstruction is not the *status quo* for several factors, from which, the lack of knowledge about the materials, systems and, as importantly, how to approach deconstruction, are the most relevant [12]. Thus, there is a need for a methodology that can help plan deconstruction: the pre-demolition audits (PreDA).

A PreDA is a systematic evaluation conducted before the demolition or deconstruction of a building or structure. Its methodology involves a comprehensive analysis of the existing building materials, components and systems to assess their condition, value, potential for recovery and environmental impacts [13, 14]. The primary purpose of a PreDA is to inform the stakeholders about the recoverable materials in the building, how to recover them, quantify waste and plan the intervention [15].

Given the importance of applying CE to the construction sector and how the PreDA can be an enabler, especially when applied to the built environment, the European Commission (EC) has developed guidelines for the structure and methodology to apply [16]. The proposed methodology [15] consists of: (i) *preliminary research:* relevant documentation is collected; (ii) *site visit*: visit to the site, measurements, and identification of recoverable materials; (iii) *inventory*: calculation of waste, type and ability to separate, and identification of recoverable materials; (iv) *final report*: all relevant information is compiled, including the quantities of waste, recoverable materials, plan of deconstruction and waste management recommendations; and (v) *quality assurance*: validation of the report with the actual data recovered from the deconstruction.

This approach aims to have a standardised report structure, facilitating its reading and interpretation by all interested stakeholders, assuring that all the main points of a PreDA are fulfilled and that the report adds value to the decision-making process and helps the recovery of materials and waste management, enabling the implementation of a CE in the built environment.

However, the development and implementation of PreDAs in the context of a CE, particularly in the construction sector, face several challenges [14], such as lack of building documentation, assuring the correct identification of recoverable materials, time and cost, lack of material marketplaces, lack of skilled labour, among others.

Despite the challenges to the development of PreDAs, several solutions have been proposed to aid, particularly in the data acquisition stage, such as scan-to-BIM, which is a process that involves capturing digital 3D representations of physical spaces or structures using laser scanning technology and then converting the data into a BIM model [17]. It can be used to aid in the development of the PreDA through the creation of a 3D BIM model to assess the building in the study. Scan-to-BIM uses several processes, starting with data acquisition (LIDAR) to capture a point cloud, that is brought into BIM software where it is analysed and converted into a 3D BIM model [18].

Also, it is possible to add another layer of imaging, specifically, photogrammetry, where photographs of the building, are applied to the point cloud gathered, adding visual information to the dimensions gathered from the LIDAR. This step can be used to, more easily, identify materials and, eventually, with the help of machine learning and artificial intelligence [19], automatically identify the building systems, types of connections, types of materials and many other characteristics relevant to PreDAs [20].

For example, Gordon *et al.* [21] used the Scan-to-BIM methodology with consumer-grade devices, where the auditor used a LIDAR device and took photographs of the relevant areas. Using photogrammetry and point cloud data analysis, was then possible to build a 3D BIM model. At this stage, the level of detail was not ideal, despite being established that the methodology had a reasonable level of success, making possible the construction of a 3D BIM model that was used for the identification of beams.

The challenges identified in the development of PreDAs can be mitigated with the adoption of digital methodologies that create a digital model of the building to be assessed, facilitating measurements and material identification and, with further development, with machine learning and artificial intelligence [19], get to a point where most of the generated wastes are automatically determined, and the recoverable materials, automatically identified. Eventually, in the future, it might be possible to automatically upload the recovered materials into a platform, during the PreDA.

Today, even with little digitalisation, the PreDAs are already central to the transition from demolition to deconstruction. In the future, considering the digitalisation and regulatory efforts, it is to be expected that PreDAs become the *status quo* when buildings reach the EoL. However, the lack of skilled labour and digital platforms, which are referred to in the following sections, are still important hurdles.

3.2 Digital Platforms

CE not only implicates that the materials are recovered but, most importantly, that they get reused in other buildings. There are already some good examples of this reutilization, such as the projects Upcycle Rows and The Resource Rows, developed in Copenhagen, Denmark [22]. These were designed using materials from EoL buildings, such as an old Carlsberg brewery from which the bricks from the façades were deconstructed in blocks and turned into the façades of the Resource Rows projects.

However, in the named cases, the deconstruction of the buildings used as source took place already knowing that those materials would be used in the projects mentioned, and the deconstruction took place with the needs of the new buildings in mind and according to a pre-determined plan and design.

In situations where this synergy, between deconstruction and new building design, is not possible, digital platforms can be an enabler for CE, especially in the form of online material marketplaces, linking the materials recovered from one site to the design team of a new building or renovation project [23].

One example of these platforms is the C+D platform, developed through EEA Grants. This platform was developed with the target of creating an online platform to facilitate the exchange of CDWs between the producers and the companies that can receive, treat and either set it to landfill or reuse it, being up- or downcycling [24].

The existence of marketplaces is very important; however, there is the issue of what information should be disclosed in the marketplace to characterize the materials.

To the "what information" problem, the answer sits with the material passports (MP). There have been several efforts in creating a standardised document, namely, among others, the proposal made by the BAMB European project [25, 26], the Madaster Material Passport, developed by a private company, Madaster, to inform their material platform [27]; and the Circularity Passport, developed by an EEA grants project between academia and the private sector in Portugal [28].

An MP, despite being useful for new materials, is even more important when trying to implement CE and develop an online material marketplace. The recovered materials need to be characterized in such a way, that the risk of a designer using these recovered materials in a new building is mitigated by the quality of the available information.

Nonetheless, with the recovery of materials and the existence of a platform that allows for their exchange, and with a proper MP with optimized characterisation, there is still the issue of how the designers can use those materials.

The design of a building has almost no limits, *i.e.* a window can have any dimensions in any material the designers want. The same applies to every other system or material, as almost anything can be made from scratch to fulfil a project's needs. However, if CE is to be adopted, the design of a new building will need to take into consideration the available materials, limiting the design options. But how can a designer know what is available, or even what will be available when the project passes from the design phase to the construction phase?

These are non-trivial challenges that designers and stakeholders face when wanting to use these materials. A potential solution is the integration of PreDAs with the marketplaces. The general idea is that the auditor identifies the recoverable materials, potentially with help from the scan-to-BIM methodologies [29], and those identified materials can be pre-characterised and immediately uploaded in the marketplace according to the report, naming a date when the materials are made available.

However, there is a need for an intermediary to do refurbishment work and then store the materials until they are needed by the project.

3.3 Skilled Labour

Typically, construction projects have several types of labour, starting at the lowest level of formation, such as bricklayers, to some of the highest, such as engineers and architects [30]. To apply CE to the sector, all of them need upskilling of some sort [31, 32]. Adding to that, creating this new economy will bring the need for new professions in the market, from people with high expertise in deconstructing to experts in data acquisition methods such as LIDAR imaging or drone operators.

Upskilling is fundamental, especially considering the shift from demolition to deconstruction practices. This shift needs a workforce specialized in not just tearing down structures but also in discerning and salvaging valuable materials [33].

Training programs are crucial in equipping workers with these skills and should focus on practical skills for deconstruction, as well as theoretical knowledge about the principles of CE. Additionally, these training initiatives must be accessible and adaptable, catering to the diverse backgrounds of construction workers [33].

The emergence of new professions is a natural progression in this evolving landscape. Roles like deconstruction specialists, material recovery analysts, scanning experts, drone operators, and CE strategists will become increasingly relevant [34]. These professions not only demand a deep understanding of construction materials and processes but also require a mindset shift towards sustainability and resource efficiency. Upskilling for these roles opens new career paths and opportunities for advancement within the industry, contributing to a more sustainable and economically viable future in construction, making it more appealing and inclusive.

For architects and engineers, upskilling involves developing a deepened understanding of sustainable materials, their lifecycle impacts and the consideration of all stages when designing. They'll need to develop skills in designing buildings that are easier to deconstruct and in selecting materials that can be reused or recycled effectively and are sustainable. This requires a shift in design philosophy, prioritizing modular and flexible constructions that facilitate deconstruction and material recovery at the EoL.

Construction workers, on the other hand, need training in specialized deconstruction techniques. Unlike demolition, deconstruction is a meticulous process that involves carefully dismantling buildings to preserve the integrity of materials for reuse. Skills in material assessment, safe dismantling practices, refurbishment and efficient sorting and storing of recovered materials will become essential.

The upskilling process also involves familiarizing the workforce with new tools and technologies that aid in material recovery and waste tracking. This includes training in the use of digital tools for inventory management and the implementation of BIM systems that can track material usage and facilitate future deconstruction planning.

Overall, upskilling current professions in the construction industry is a critical step toward achieving the goals of CE. By equipping the existing workforce with new skills and knowledge, the industry can make significant strides in reducing waste, conserving resources and, in the end, building a more sustainable future.

3.4 Discussion

The application of CE to the built environment is, as shown, a challenge for everyone involved. Thus, new solutions and paradigm changes are needed. However, the development of new solutions is not enough in itself, as these solutions need to work symbiotically to help the construction sector shift the paradigm from linear to circular.

Figure 1 shows how CE can be applied to the construction sector while showing the main information and material flows and attributing the main enablers of CE to specific stages or tasks within the processes [34, 35].

This system presents a CE approximation to the construction sector, demonstrating the level of complexity in applying it to this sector. It also demonstrates how the identified enablers can help this paradigm shift, from the initial upskilling of the labour force, using technology in the development of the PreDAs to, finally, using a marketplace to exchange the materials.

The main idea behind Fig. 1 is that, for the application of CE in the construction sector, two different flows should be considered: an information flow, and a material flow.

The information flow is as follows:

1. During the inventory phase of the PreDA (step 01), the auditor identifies the recoverable materials which can (if chosen) immediately be placed into a marketplace with general information such as materials, characteristics and expected time to be made available, before full characterization.
2. After the deconstruction and the materials are recovered (step 04), the materials are refurbished and fully characterised, creating the MP (step 05) to input into the marketplace (the materials might have been reserved or not).
3. Designers use the marketplace to find suitable materials for the building they're working on, this process is iterative, and the designers might change the design, so they can use a material, reserve it, and then change the design and revoke the reservation (exchange between steps 06 and 08).

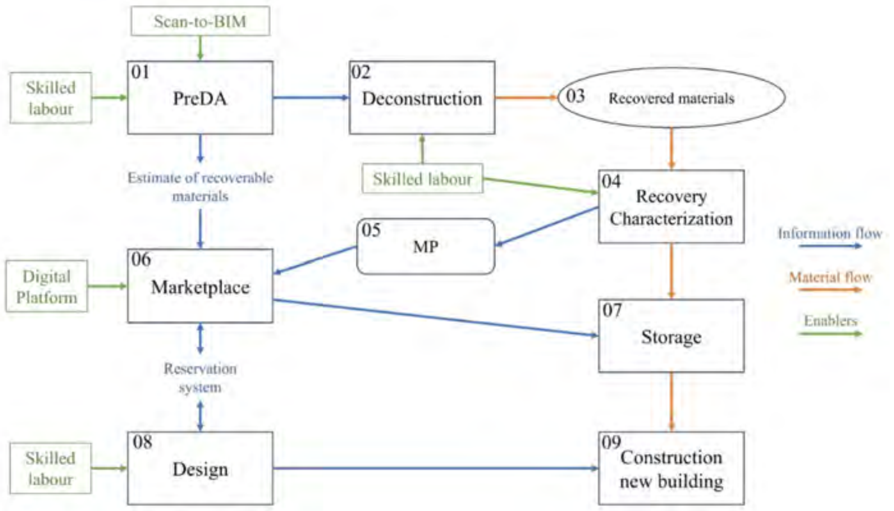

Fig. 1. Enabling factors and their application to information and material flows in CE (adapted from [34, 35]).

4. In the meantime, the materials are stored either by some intermediary or by any of the stakeholders (step 07).
5. The construction takes place under the final project and uses the materials already defined and, possibly, stored, waiting for use.

The material flow is similar to, and follows the information flow already described:

1. At the deconstruction (step 02), the materials identified on the PreDA are recovered from the building (step 03) with the help of skilled labour.
2. The materials are refurbished and characterised (step 04) by skilled labour.
3. After the refurbishment and full characterization, the materials are stored until use (step 07).
4. Finally, the materials are used as defined by the design, in the project (step 09).

Here, and as already mentioned, PreDA are an enabler through their function of identifying materials, quantifying waste and preparing and planning the deconstruction task. The digital platforms, in the form of marketplaces, are enablers due to the ability to exchange information (and then materials) between stakeholders. And, finally, the need for a specialized workforce, makes upskilling of labour an enabler.

4 Conclusion

This paper has explored the transformative potential of incorporating Circular Economy (CE) principles into the construction industry, with a focus on the End-of-Life (EoL) phase of buildings. The model discussed encompasses pre-demolition audits (PreDA), digital platforms, and the upskilling of labour, presenting a paradigm shift in how we might approach construction and demolition in the future.

PreDAs emerge as central in this model, as they allow for an informed, strategic approach to material recovery, by identifying reusable materials before demolition, making deconstruction possible and attractive.

Digital platforms bridge the gap between recovered materials and new construction projects. These platforms can serve as marketplaces, fostering the flow of recovered materials, essential for the CE in the construction sector.

Furthermore, the importance of skilled labour cannot be overstated. Helping workers to adapt to new construction practices is crucial for the successful implementation of CE principles in the sector. Skilling the workforce will enhance the quality and quantity of material recovered, while also providing a much-needed pathway for sustainable and inclusive employment in the sector.

In conclusion, the integration of CE into the construction industry is not just a theoretical concept but a necessary step towards sustainable development. This approach does not only address environmental concerns but also offers economic and social benefits, setting a blueprint for a sustainable, resilient, and circular construction sector.

The future of the construction industry is one where sustainability is not an afterthought but a foundational principle. The journey towards circular economy to improve sustainability in construction is complex and challenging, but with collaborative efforts, technological innovation, innovative thinking, and full commitment, it is undoubtedly achievable.

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Digitalisation and BIM for Circular Design and Evaluation in Construction

The Role of BIM in Supporting Circularity: A Conceptual Framework for Developing BIM-Based Circularity Assessment Models in Buildings

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Abstract. The simultaneous evolution of the construction sector towards the circular economy and digitalization is widely recognized and endorsed by both policy initiatives and academic discourse. In this dynamic landscape, research efforts are focused on creating automated tools and models to facilitate the implementation and monitoring of circularity in buildings, thereby enhancing efficiency and effectiveness of decision-making processes. Building Information Modelling (BIM) stands out for its acknowledged capabilities in data storage and process automation, making it a compelling platform for achieving these objectives. This paper aims to establish a conceptual framework that addresses the challenge of developing BIM-supported tools and models for promoting circularity in buildings. The primary goal of the proposed framework is to assist tool developers and professionals in the construction sector, providing them with a systematic approach to integrate circularity aspects into BIM for efficient and automated assessment processes. To achieve this, the study critically analyzes five existing BIM-based circularity tools and models from previous studies, elucidating the key stages and providing detailed steps for their development. The paper concludes by emphasizing the main barriers hindering the development and automation of circularity tools within the BIM framework. This comprehensive exploration contributes to the ongoing discourse on sustainable construction practices, offering valuable insights for practitioners, researchers, and policymakers striving to advance the integration of circular and digital principles in the construction industry.

Keywords: BIM · Circular Economy · BIM-based Circularity Assessment · Conceptual Framework · Circular Buildings

1 Introduction

The construction industry faces numerous challenges, as it stands as one of the major contributors to natural resource consumption and environmental impact. Additionally, the issue of construction and demolition waste (CDW) resulting from demolition activities

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during the end-of-life stage exacerbates the industry's resource, energy, and greenhouse gas (GHG) intensity. Consequently, there is an urgent need to explore more sustainable approaches to transform the industry, making it a top priority on both International and European agendas for achieving sustainable development.

The European Green Deal, part of the sustainable growth agenda, has spearheaded a green transition, leveraging the challenge of climate change to create a unique opportunity. According to the European Commission, this transition is crucial for two primary objectives: firstly, mitigating the consequences of climate change and environmental degradation, and secondly, enhancing the European Union's (EU) energy self-sufficiency [1]. At the core of the European Green Deal's roadmap lies the Circular Economy (CE), a critical policy area designed to promote the efficient use of resources and stimulate sustainable economic growth. This initiative places particular emphasis on seven resource-intensive sectors, including construction and building [2].

Within the construction industry context, numerous studies advocate for the development of indicators to measure the implementation of CE principles, especially in expressing the circularity of individual buildings [3]. Decision-makers in the industry, including architects, engineers, and contractors, require tools that can assist them in harnessing the value of CE approaches. These tools should provide a systemic view of the effects of material circularity specifications and circular design aspects.

On the other hand, Industry 4.0 marks the world's fourth industrial revolution, aspiring to bring about a significant transition. This transition encompasses profound changes in the design, production, operation, and servicing of manufacturing systems and products [4]. Termed as the digital transition, this transformation relies on various innovative technological advancements. These include strategic information and communication approaches, Cyber-physical systems (which involve additive manufacturing supported by sensors and robots), network communications, simulation, modeling, and virtualization techniques (such as BIM, Virtual and Augmented Reality), as well as data collection and management through big data analytics and cloud computing. Additionally, this transition aims to support human workers by integrating robots and other intelligent tools.

The EU's commitment to fostering a sustainable yet competitive economy has gained significant importance through its embrace of the objectives of Industry 4.0 and the CE, recognizing their pivotal influence on the economy [5], environment, and society. The tandem of green and digital shifts is acknowledged as the twin transition, highlighted by the EU agendas as pivotal for shaping the EU's future, encapsulating both green and digital objectives. The synergies between these transitions amplify their individual impacts. The digital shift holds promise in bolstering the green transition by transforming current business models into new approaches that actively pursue sustainable development across environmental, economic, and social pillars. This is achieved by supporting efficient processes, fostering a deeper understanding, and facilitating comparisons among alternatives to effectively and efficiently identify optimal solutions.

This paper aims to demonstrate the synergistic alignment of twin transition objectives, explicitly focusing on the application of BIM to facilitate circularity implementation and monitoring. The study unfolds in a structured manner, providing readers with a cohesive and clear understanding of the study's objectives, methodologies, outcomes, and challenges. The first section delves into a comprehensive background overview, exploring the motivations behind the research. The second section outlines the methodology employed to meet the study's objectives. The third section presents analysis results and introduces the conceptual model's structure for seamlessly integrating circularity assessment into BIM. Finally, the fourth section addresses challenges, highlighting barriers encountered in the process of circularity assessment and integration into BIM.

2 Methodology

The study endeavors to elucidate the pivotal role of BIM in facilitating the implementation and evaluation of circularity principles within the construction sector. Its primary aim is to establish a conceptual framework tailored for stakeholders keen on harnessing BIM and digital technologies to streamline their thought processes.

The methodology employed to attain this objective involves an in-depth analysis of five pre-existing studies that have effectively utilized BIM capabilities to craft functionalities supporting the integration and assessment of circular practices in construction. Building upon this analytical foundation, a comprehensive conceptual framework delineating intricate steps is proposed to develop models for assessing circularity. The framework accentuates and illustrates essential steps while addressing potential barriers and challenges inherent in the process.

In essence, the study furnishes a roadmap for stakeholders seeking to capitalize on the capabilities of digital technologies and tools for supporting circular practices. It serves as a brief guide to inform decision-making processes aligning with their overarching goals.

3 Results

3.1 BIM for Circularity Assessment

The recent paradigm shift toward a design-centric and information-centric approach in building construction has led to the widespread adoption of BIM [6]. BIM can be defined as an integrated process involving collaborative efforts from stakeholders to create a parametric virtual model representing a building with the aim of facilitating effective management throughout the building lifecycle, from planning and design through operation and maintenance to end-of-life decommissioning [6].

Parametric representation within BIM ensures bi-directional connectivity with reality, supporting changes that occur along the building's lifecycle. This connectivity is crucial, as alterations to one element can influence connected elements, ultimately impacting the overall building integrity [7]. The increasing implementation of BIM for various purposes, such as 3D building visualization, building performance analysis, cost estimation, and facility management, underscores the necessity for genuine innovation within the construction industry to be BIM compliant [6].

In the context of BIM, a building model is portrayed as a database, creating opportunities for incorporating diverse sustainability analyses [8, 9]. BIM serves as a valuable instrument for conducting environmental or economic assessments considering the entire lifecycle of a building. These assessments may be required multiple times over the building's lifespan [8]. Various tools have been developed to integrate sustainability objectives into BIM, enhancing calculation processes and supporting decision-making. An example is the IMPACT (Integrated Material Profile And Costing Tool) tool by the Building Research Establishment (BRE), designed to integrate Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) into BIM [10]. Models compliant with IMPACT, such as One Click LCA, conduct assessments in accordance with sustainability standards. Numerous studies have highlighted BIM's use in addressing environmental and economic sustainability concerns during different lifecycle stages of buildings [6]. Other BIM-based tools developed to improve sustainability include the BIM-based design optimization method for improving building sustainability [11].

Utilizing BIM for evaluating circularity in buildings represents a relatively novel area, with limited literature offering insights into BIM's potential in this context. Nonetheless, the significance of this research direction is widely recognized among scholars, researchers, stakeholders, and professionals. Notably, there is a noticeable gap in existing studies that specifically address circularity objectives, particularly during the deconstruction stage and the planning of circular paths from the early design phase. This gap may be attributed to the recent attention to the CE concept. However, there is a growing interest in exploring this research direction to create tools for assessing circularity in buildings. The incorporation of BIM is seen as a pivotal element to enhance efficiency in information accumulation and calculation across different lifecycle stages and for various assessment purposes. To fulfill the objectives of this study, this section delves into five prominent BIM-based tools that have been developed to evaluate and guide the implementation of circularity in buildings.

BIM-DAS, 2015. In a study by Akinade et al., the BIM-based De-constructability Assessment Score (BIM-DAS) was introduced as a tool to evaluate a building's deconstructability, starting from the design stage [12]. The model employs a mathematical approach, incorporating efficient material requirement planning and Design for Deconstruction (DfD) principles. The BIM-DAS model was integrated into Autodesk Revit software to facilitate the comparison of deconstructability potential alternatives during the design phase. The combination of the Deconstruction Score and Recovery Score determines the DAS Score. BIM played a critical role in this model by facilitating circularity data storage within project elements through custom parameters. Additionally, it aided in the generation of bills of quantities and automated the calculation processes. This use of BIM technology ensures an inclusive assessment of deconstructability factors, enabling informed decision-making early in the project lifecycle.

BWPE, 2018. In 2018, Akanbi et al. introduced the BIM-based Whole-life Performance Estimator (BWPE) as a valuable tool for construction practitioners [6]. This innovative system facilitates informed decision-making by assessing the salvage performance of structural components, including reusability and recyclability. Importantly, it provides insights right from the design phase and at any stage throughout the building lifecycle. The BWPE employs a mathematical modeling approach, grounded in the principles of Weibull reliability distribution for manufactured products. Its functionality leverages various BIM capabilities, such as modeling, visualization, and material databases. The model has been seamlessly integrated into the Autodesk Revit BIM software as an add-in, utilizing multiple programming languages and the Revit Application Programming Interface (API). To enhance user experience, the BWPE visualizes data through a 2D line chart embedded in the Revit interface. The model's efficacy was rigorously evaluated using three structural design specifications derived from a real-life building case study. This comprehensive assessment underscores the practicality and reliability of the BWPE in supporting decision-making processes within the construction industry.

D-DAS, 2019. In a study be Akanbi et al. [13], a BIM-based Disassembly and Deconstruction Analytics System (D-DAS) was developed, drawing inspiration from earlier tools such as BIM-DAS [12] and BWPE [6]. The purpose of D-DAS is to offer an end-of-life performance assessment for buildings, starting from the design stage. The system is designed with a four-layer architecture, each layer interconnected to form a cohesive system that integrates their relationships and interactions. These layers include (i) the Data Storage Layer, (ii) the Semantic Layer facilitating data exchange and provisioning to the application layer, (iii) the Analytics and Functional Models Layer where the system's functionalities are developed, and (iv) the Application Layer enabling user interaction with the system. D-DAS, implemented as a Revit plug-in, provides three key functionalities supporting end-of-life circularity. These functionalities are: (i) Building Whole Life Performance Analytics (BWLPA), (ii) Building Element Deconstruction Analytics (BEDA), and (iii) Design for Deconstruction Advisor (DfDA). Leveraging both mathematical approaches and BIM capabilities, the D-DAS model incorporates machine learning in its data storage layer. This allows the system to be trained with historical data on deconstruction practices, enabling it to predict material destinations such as reusable, recyclable, or disposal. Functioning as a decision-support tool for construction industry practitioners and professionals, D-DAS facilitates the comparison of design alternatives. It enables the appraisal of the preferred option based on project circularity objectives.

A BIM-Based Framework to Visually Evaluate Circularity and Life Cycle Cost of Buildings, 2019. In this work, Biccari et al. employed BIM to create a methodological framework for assessing the circularity and total life cycle cost (LCC) of building projects at various stages of their lifecycle [8]. The aim was to identify optimal solutions by comparing alternatives. To implement their framework, the scholars utilized multiple BIM capabilities, developing an Autodesk Revit add-in that automated volume estimations for bills of quantities (BoQ) generation. They also employed Product Breakdown Structures (PBS) to define the Work Breakdown Structure (WBS) and established links with other software tools for Cost Breakdown Structure (CBS). Additionally, custom parameters were introduced, complementing the standard ones offered by BIM software. The add-in facilitated the visualization of circularity levels for different groups of components, along with their associated life cycle costs. This visualization aimed to evaluate the Circular Business Model (CBM) using a straightforward mathematical approach based on the CBM's circularity value, recyclable volume, and Life Cycle Assessment (LCA) performance in terms of CO_2 emissions. Components were grouped based on their circularity characteristics, such as the share of their recyclable volume. The LCC was calculated using the CBS, applying net present value for each component. The resulting visualization, employing different colors to represent various levels of circularity and LCC values, allowed users to make informed decisions about the desired solution and understand the trade-offs involved between these two variables.

BCA, 2020. In 2020, Zhai introduced a BIM-based circularity assessment (BCA) framework [14], with automated circularity assessments spanning various building composition levels. This innovative approach adopted a bottom-up progression, starting from the material level, progressing through the product then system levels, and culminating in a comprehensive assessment of the entire building level. After delineating key indicators, informed by a literature review focusing on disassembly potential and circular material flow, the BCA framework was established and subsequently automated using Dynamo—a visual programming software compatible as a plug-in for BIM platforms like Autodesk Revit. Dynamo's prototyping capabilities were instrumental in creating an automatic connection between Revit and an external database. This connection facilitated the calculation of BCA metrics and the visual representation of results in Revit through charts, along with the application of colour overrides to elements. The development of the BCA model harnessed various BIM capabilities, including the creation of element families with shared parameters, customization of parameters, effective data storage, and automated calculations. These functionalities were further enhanced by seamless integration with an external database, emphasizing the model's efficiency and accuracy in circularity assessments.

3.2 A Conceptual Framework/Structure of Integrating Building Circularity Assessment into BIM

Expanding on the analysis of the preceding five BIM-based tools, a conceptual framework has been formulated for the development of a circularity implementation and assessment tool, specifically designed for seamless integration within the BIM environment. This framework encompasses crucial steps for constructing a comprehensive circularity model, encompassing the necessary requirements and facilitating their digitization, as well as the automation of indicators and variables for calculation purposes. The conceptual structure is briefly summarized in Fig. 1, and the necessary steps are elaborated upon in detail as follows.

To effectively develop a circularity assessment tool or model and seamlessly integrate it into BIM, a systematic approach must be adhered to. This process commences with Stage 1, wherein the primary focus lies in defining the objectives and motivations underlying the integration of the chosen method or tool. This entails a meticulous articulation of the problem or challenge at hand, outlining the desired outcomes, and elucidating the expected results in terms of the tool's utility for potential users such as practitioners, contractors, and end-users. Emphasis should be placed on how the tool facilitates decision-making concerning the assessed subject.

Equally crucial at this stage is a comprehensive understanding of the background, aim, and scope of the subject earmarked for digitization and automation. This entails defining the concepts, principles, and circularity aspects to be assessed and measured by critically analyzing existing models and building upon prior work to identify influential factors. This step serves as a foundation for selecting the most appropriate method to achieve the defined goals.

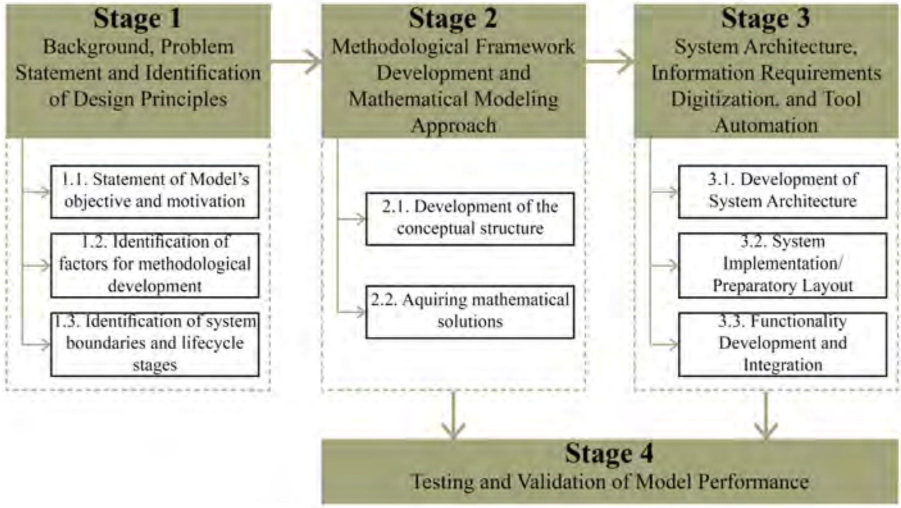

Fig. 1. A Conceptual Framework of BIM-based Circularity Assessment Tools. Source: Authors' own elaboration.

Ultimately, it is imperative to delineate the system boundaries of the subject under assessment, clearly specifying the lifecycle stage or stages to be considered. Details should encompass the extent of circularity of materials, indicating its commencement (e.g., former use of materials, number of previous uses, supply chain) and termination (destination of materials leaving the building loop and the subsequent loops to be integrated, considering the next use or multiple next uses). Other boundaries should also be distinctly outlined, specifying the particular aspects to be addressed without veering into unrelated considerations.

Stage 2 of the framework is dedicated to the development of the methodological framework and mathematical modeling approach. This phase entails creating the conceptual structure of the methodology, which includes formulating a mathematical modeling approach. The process involves defining essential variables and indicators based on factors and parameters identified in the initial stage. This includes establishing relationships and specifying equations. Furthermore, articulating key assumptions is a crucial part of this stage.

Once the conceptual structure is established, mathematical and computational solutions are derived for the model using algorithms. These solutions are then interpreted in relation to the defined variables, parameters, and assumptions. It is important to highlight that, in many instances, tools are constructed on the foundations of prior ones incorporating existing indicators in newly proposed models.

Stage 3 focuses on the development of the system architecture, digitization of information requirements, and tool automation. During this phase, the system is seamlessly integrated into BIM software by identifying the necessary additional software, programming languages, and skills. This integration ensures a smooth data flow, exchange, and access. BIM software such as Revit is carefully chosen and assessed for its capabilities. Tools for programming, mathematical simulation, and assessments are incorporated, while connectivity with tools like Life Cycle Assessment (LCA) is considered to enhance integration. Custom parameters are defined to tailor the system to specific needs and augment BIM model elements.

In the System Implementation/Preparatory Layout phase, the BIM model undergoes development or enhancement for seamless integration. This involves achieving an appropriate Level of Detail (LOD) and considering standard parameters like parametric elements. Additional information, such as custom parameters covering material specifications, dimensions, and lifecycle data, is integrated into the 3D geometric model. Information requirements for calculations, including BoQ, are prepared, alongside the setup of external databases for efficient data management.

The Functionality Development and Integration step involves creating system functionalities that can serve as add-ins to BIM software. Relevant programming languages and tools, including the Application Programming Interface (API), are utilized to establish an application interface that facilitates user interaction with the system. Various activities within this step include establishing connections with external databases (if applicable) to enhance data integration and developing visualization forms for presenting results. These forms may include charts, tables, graphics, and element overrides with colors, all aimed at ensuring effective communication of information.

Stage 4 in the model development process focuses on the Testing and Validation of Model Performance, representing the final phase. The primary objective at this stage is to conduct comprehensive testing and validation to ensure that the developed model meets the desired performance standards. Employing a case study, the model is simulated, and its results are meticulously examined. Conclusions are drawn based on the findings of this evaluation, which plays a crucial role in identifying any shortcomings or areas for improvement. Necessary modifications are then incorporated to enhance the model as needed. It is essential to note that Stage 4 can also occur after Stage 2, where the mathematical approach of the model is simulated using a typical dataset to validate functionality and interpret results. However, the timing of this stage depends on the project plan and whether there is a decision to test the model tool after its development but before full automation.

4 Discussion and Conclusions

This study presents a conceptual framework for the development of BIM-based circularity implementation and assessment tools. The proposed conceptual structure is derived from a critical review of five existing BIM-supported models for circularity. The framework outlined in this work offers valuable insights and guidance for tool developers and CE practitioners in the construction sector. It provides necessary steps and considerations for the development of circularity tools with automated functionality utilizing the BIM. This is crucial because, while the automation of traditional dimensions of sustainability (particularly environmental and economic aspects) has been extensively explored in previous studies, the integration of CE principles into BIM is still evolving. Numerous initiatives are underway to support this research direction, aiming to bring key benefits to the industry. However, a more in-depth analysis of more BIM-based tools is essential for refining the proposed framework.

Developing circularity tools in the BIM context is a complex task, presenting challenges in methodological development and automation. Effective CE implementation in construction requires knowledge of the status and quality of building materials, especially for pre-existing buildings where material information may not be readily accessible. Incorporating circularity throughout the lifecycle of building materials is complicated by their previous loops, making it uncertain to predict their destinations after leaving the assessed building loop. Assumptions are necessary in the tool's development process to address this uncertainty. Similarly, planning the full lifecycle of buildings requires assumptions due to changing circularity factors influenced by market conditions, policies, and other factors.

Regarding BIM integration, it is noteworthy that the automation and digitalization of circularity processes' evaluation in BIM environments demand thorough preparatory and well-structured work, which takes time. However, once the process is automated, it can be applied repeatedly, providing efficiency and real-time assessment capabilities, contributing to efficient and effective decision-making processes.

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Utilising BIM on LCC to Enhance the Sustainability of Saudi Residential Projects Through Simulation. A Case Study at the Kingdom of Saudi Arabia

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Abstract. There is a growing emphasis in current global construction sector for the incorporating of sustainability ideas into design and construction practices. This present paper investigates the considerable impact of using Building Information Modelling (BIM) techniques to address sustainability and financial concerns in a residential project in the Kingdom of Saudi Arabia (KSA). We propose to further embedding BIM 3D modelling and the development of alternative design scenarios for optimising Life Cycle Cost (LCC) and Life Cycle Assessment (LCA). Four scenarios are assessed using Green Building Studio (GBS) for whole-building analysis, and specific design units are assessed using One Click LCA, which is integrated into Revit. The significance of the study relies on merging of BIM and LCC to improve the sustainability of residential developments at the KSA. It also intends to optimise resource efficiency, reduce environmental impact, and increase cost-effectiveness throughout the whole life cycle of residential structures by using simulation approaches. The findings will benefit industry stakeholders by encouraging sustainable practises that inform decision-making processes in the context of Saudi residential development.

Keywords: Building Information Modelling (BIM) · Life Cycle Costing (LCC) · Life Cycle Assessment (LCA) · Sustainability · Simulation · Optimisation · Residential Projects · Kingdom of Saudi Arabia (KSA)

1 Background

The significance of sustainability worldwide in the construction industry has grown impressively in recent years due to the growing awareness of environmental concerns and the collective acknowledgment of the significant impact of industrial activity on natural resources [1]. The dynamic nature of the construction industry, combined with the constant fluctuation material prices, labour costs, and regulatory changes, contributes to the ongoing problem of complex management and costs increase of residential projects [2, 3]. The complexities of synchronising multiple components of the construction process,

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such as material specifications, labour requirements, and project schedules, highlight the difficulties for resolving and reducing the financial issues associated with residential construction [4–6].

BIM has transformed the construction and design industry by offering a detailed digital depiction of a building throughout its entire lifecycle. One of the most significant benefits of BIM is the impact it has on LCC management [7, 8]. BIM enables stakeholders to make educated decisions regarding a building's design, construction, and operation through the integration of diverse data sources with modelling, hence providing ability to foresee critical scenarios [9–11]. The use of BIM to optimise LCC entails creating a centralised digital model that captures all critical information about a structure, from conception to demolition [12–14]. This model functions as a dynamic database that stakeholders can access at various stages of the building's life. Architects, engineers, contractors, and facility managers may work together in real-time to make informed decisions that consider the long-term financial ramifications of each option.

BIM integration in LCC analysis has shown potential for improving the efficiency and accuracy of the cost estimation throughout the life of construction projects. However, significant challenges remain, which need a deeper comprehension of the elements influencing the effective application of BIM technologies for LCC optimisation. It is therefore critical to address data integration challenges to enable seamless information interchange among various BIM platforms, as well as overcoming cooperation barriers among project stakeholders, while fully embedding BIM into project management workflows. This is important as BIM and Circular Economy principles interact at the forefront of sustainable and efficient construction practices [15–18]. For example, BIM enables stakeholders to cooperate during the structure's full lifecycle. When combined with Circular Economy concepts, BIM becomes a strong tool for optimising resource use, reducing waste, and encouraging material reuse and recycling. The emphasis is on creating structures that can be readily disassembled, reused, or recycled at the end of their life cycles [19–21]. BIM enables efficient disassembly and reassembly procedures by facilitating the tracking and documenting of materials and components [22].

This integration between BIM and circular economy is still underexplored in the building industry, an instance is the insufficient integration of LCA data into BIM processes, which impedes a thorough knowledge of the environmental effect of construction projects across their entire life cycle. To date, the circularity potential of construction materials and components is underutilised in BIM because the industry frequently lacks standardised databases and procedures for analysing and selecting materials based on their recyclability or reusability [23–25]. BIM simulation provides many benefits, one of which is the ability to create a virtual, three-dimensional model of a building, allowing for comprehensive simulation of various design scenarios and accurate cost estimation throughout the entire life cycle [26]. Compatibility concerns between different BIM platforms and standards can also complicate information interchange among project stakeholders, thereby limiting the smooth flow of data required for correct LCC calculations [27, 28].

The present study demonstrates the application of BIM tools in optimising LCC and LCA to meet the challenges that require an integrated approach, incorporating advanced technologies, strategic planning, and innovative methodologies. It aims to exploit the synergies among the design, construction, and operational phases by integrating various techniques, thus achieving a comprehensive understanding of a building's life cycle sustainability. The paper addresses the increasing costs and inefficiencies in residential construction, exemplified by a case study of a residential project in KSA. Its primary objective is to assess how strategic BIM tool utilisation can offer effective solutions for optimising LCC and LCA in residential buildings.

2 Methodology

The research methodology employed in this study aims at addressing the challenges of rising costs in residential construction projects through the integration of BIM tools. The approach adopted for this research involves a multi-step process, combining 3D modelling, simulation, and analysis to optimise LCC and LCA as shown in Fig. 1. The primary BIM tool utilised for 3D modelling was Autodesk Revit 2023, which was selected given its advanced capabilities in creating detailed and accurate building models.

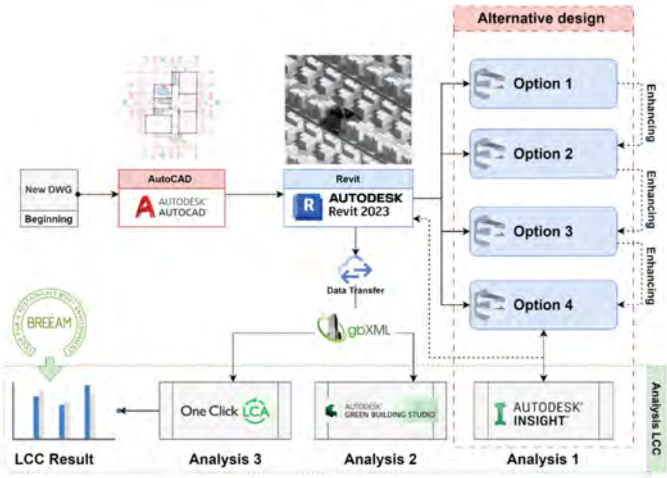

Fig. 1. On the LCC Analysis Methodology.

To initiate the methodology, an existing 3D model of a residential house was created using Autodesk Revit 2023 to determine the technical specifications of the project's materials. This model played a pivotal role in generating the Bill of Quantities (BoQ), correcting omissions observed at the 2D level, thereby contributing to more precise cost estimations. The selection of Revit as the primary software aimed at not only stimulating the design process, but also providing a platform for 3D concept design, physical simulation, and the monitoring of building performance. Following the creation of the 3D model, four alternative design scenarios were developed, each varying wall and floor specifications. These alternative scenarios were crucial in estimating the energy costs associated with LCC. Autodesk Insight, a comprehensive tool integrated with

Revit, was employed to perform the analysis, considering the energy and environmental performance of each scenario. Additionally, Autodesk Green Building Studio (GBS), a whole-building analysis software program, was utilised for a detailed analysis of the four scenarios based on actual model data, local energy sources, and weather data. As a final step in the methodology, the model was transferred to One Click LCA, a web-based analysis service integrated with Autodesk Revit. This platform was instrumental in conducting a detailed analysis of Scenario 1 in the actual design unit and Scenario 4 after enhancing its specifications. The analysis encompassed factors such as Life Cycle Cost, Life Cycle Assessment, BREEAM sustainability criteria, and building circularity.

3 Case Study and Data Analysis

The Residential Development Project is a large project that includes 900 residential structures that address the growing need for housing in the KSA in addition to the necessary utilities including fences, exterior gates, and groundwater tanks. Each residential unit has three bedrooms, a sitting room, a living room, three bathrooms, and a kitchen on one and a half storeys. Each unit has a total building space of roughly 294 m^2 (see Fig. 2).

Fig. 2. Views of the Site Plan: Ground and First-Floor Designs.

The residential project has challenges, most notably delays and associated cost increases. The project was originally slated to be completed in 2012, but a three-year delay pushed the completion date to 2015. The main cause of this delay was a two-year extension granted to meet an expanded project scope. The first extension, authorised for 16 months, resulted in a $7,019,257.98 budget increase. Changes in contract conditions and the introduction of goods not originally covered prompted this augmentation. A subsequent 18-month extension increased expenditures by $1,635,840.5, bringing the total budget rise to $8,672,721.81. This delay of 1003 days represented a 92.87% increase over the original contract time. The necessity for an effective project analysis strategy became clear, motivating the look into ways, such as the integration of BIM tools, to optimise LCC and LCA and minimise such issues.

By altering the specs of the walls and flooring, four distinct scenarios were created, introducing a range of design options for the residential construction. The goal was to estimate the energy expenses associated with LCC for each scenario using BIM tools, specifically Autodesk Revit 2023 (see Fig. 3).

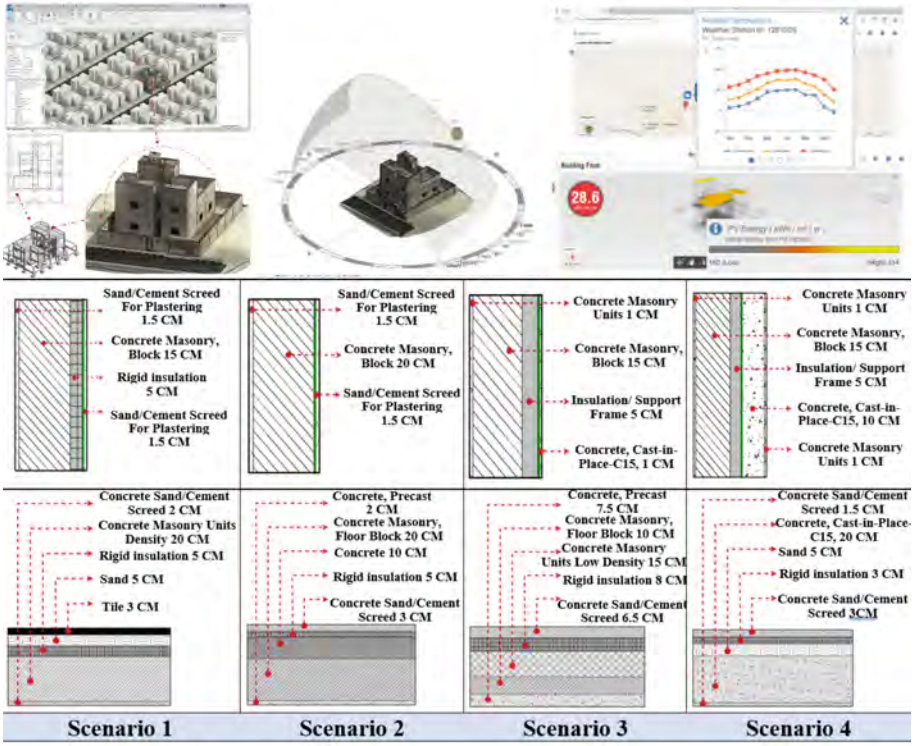

Fig. 3. Differentiated Design Options.

4 Results and Discussion

The study utilised AutoDesk® Revit 2023 to create a 3D model of a residential project, enhancing the accuracy in determining technical specifications of materials. This contrasted with the 2D level, where quantity omissions were noted. The 3D model aided in preparing the Bill of Quantities, leading to significant time and cost savings of approximately \$8.67 million. In addition, the analysis of the four alternative design scenarios yielded insightful results, shedding light on the varied impacts of design choices covering energy efficiency, LCC, and environmental sustainability. The presentation of results for each scenario is outlined in Table 1.

For expanding the LCC analysis to a 50-year period from the initial 30-year lifecycle, it is essential to adjust the current LCC data. The original calculation uses a 6.1% discount

Table 1. Results from the alternative scenarios.

	LCC*	Annual CO_2 Emissions (Onsite Fuel)	Energy Use Intensity (EUI)
Scenario 1	$71,739	4.3 Mg	1,715 MJ/m^2/year
Scenario 2	$62,503	4.1 Mg	1,520 MJ/m^2/year
Scenario 3	$54,555	3.6 Mg	1,238 MJ/m^2/year
Scenario 4	$43,529	2.3 Mg	908 MJ/m^2/year

* The estimation is based on a projected lifespan of 30 years and applies a 6.1% discount rate for expenses. It does not consider transmission losses or the possibilities of renewable energy and natural ventilation.

rate, which is retained in the extended analysis. This calculation relies on a formula that determines the present value of future costs Eq. (1):

$$PV = \frac{C}{(1 + r)t} \tag{1}$$

PV = the present value;
C = the future cost;
r = the discount rates;
t = the time in years.

As a result of this formula, LCC can be recalculated over the next 50 years while maintaining the basic assumptions of the original analysis. Based on a fixed annual cost and a discount rate of 6.1%, the LCC for each scenario over 50 years is as follows: Scenario 1: $76,343.84, Scenario 2: $66,514.99, Scenario 3: $58,056.82, and Scenario 4: $46,323.08. A modest increase in LCC can be seen by extending the analysis from 30 to 50 years. Figure 4 shows that the Level(s) lifecycle assessment (EN15804+A1) reveals that a low energy/carbon building (Scenario 4) significantly reduces environmental impact in all categories compared to the baseline of Scenario 1. The greatest emissions reduction is seen in modules A1–A3 materials stage encompass the supply of all materials, products, and energy, along with waste treatment until reaching the end-of-waste state or final residue disposal, focusing exclusively on the building and its components during the product stage, excluding items like furniture or appliances, with emissions dropping from 143,687.72 kg CO_2e in Scenario 1 to 103,258.82 kg CO_2e in Scenario 4. This demonstrates the environmental benefits of low energy/carbon building strategies. Specifically, emissions from external walls decrease by about 50.87%, from 72,058.26 kg CO_2e in Scenario 1 to 35,425.81 kg CO_2e in Scenario 4.

There will be 51.6% of the total material quantity that is recoverable as-is (with a recycling content of 3.1% at stage A), and 7.8% that can be reused. The scenario differs significantly in Scenario 4, however: 9.9% of the materials will be returned (see Fig. 5).

The comparison of the four alternative design scenarios provides an understanding of the implications associated with different design choices in residential construction. Scenario 4, which embraced circular design principles, emerged as a compelling alternative by delivering competitive energy efficiency highlighting the economic viability and sustainability benefits of integrating circular principles into construction practices. The

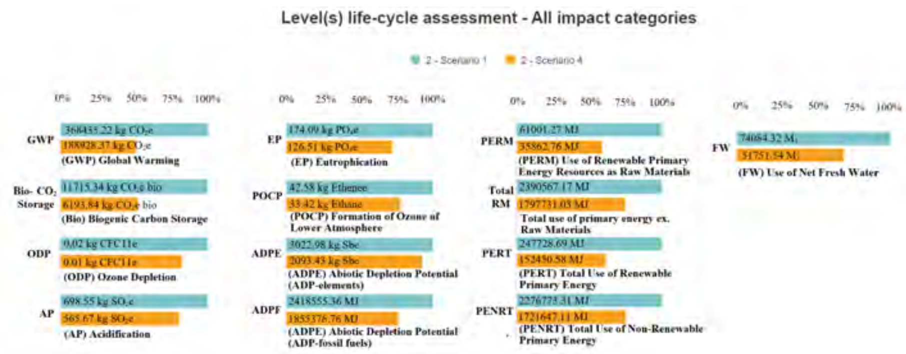

Fig. 4. Comparison of the life cycle assessment (LCA) Scenario 1 with Scenario 4.

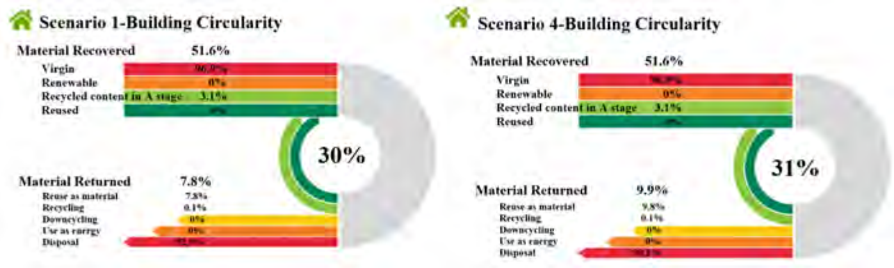

Fig. 5. The outcomes related to the circularity of the building in both Scenario 1 and Scenario 4.

scenario not only exhibited the lowest LCC but also demonstrated a substantial reduction in carbon dioxide (CO_2) emissions, emphasising the potential of circular design to mitigate the environmental impact of residential construction. This outcome aligns with the growing emphasis on sustainable and environmentally conscious construction practices. Scenario 4's cost-effectiveness and sustainability have been enhanced by the strategic integration of LCC analysis through BIM. BIM tools, particularly Autodesk Revit, are critical in modelling and simulating numerous design situations. Engineers could use BIM to thoroughly analyse the technical requirements of project materials, allowing them to create alternative design scenarios. This process enables a thorough examination of the effects of various design options on energy efficiency, costs, and environmental performance. BIM emerges as a critical instrument in aligning construction practices with sustainable development objectives, encouraging a complete approach to building design and operation by optimising LCC and LCA characteristics.

5 Conclusions

This study underlines the critical significance of BIM tools in tackling the issues associated with escalating construction costs in residential construction projects. The study illustrates the effectiveness of BIM in optimising LCC and LCA by applying an extensive approach that incorporates 3D modelling with the appropriately selected software.

The case study of the large-scale residential development project in KSA provides useful information into the details of construction processes, such as delays and cost escalation. The research demonstrates clear benefits from the integration of BIM tools, particularly in the creation of the Bill of Quantities, resulting in significant time and cost savings. The examination of different design scenarios demonstrates BIM's potential to increase energy efficiency, reduce environmental impacts, and, ultimately, contribute to the production of cost-effective and ecologically friendly built environments. A comprehensive analysis of different design scenarios using BIM tools is presented, focusing on their impact on LCC and environmental sustainability in residential construction. The study identifies substantial savings and efficiency improvements, particularly in a scenario incorporating circular design principles, which resulted in the lowest LCC and a remarkable reduction in CO_2 emissions. This scenario also showed a significant decrease in annual CO_2 emissions and Energy Use Intensity (EUI), underscoring the advantages of integrating circular design in construction.

In the future, it is necessary for stakeholders in the construction industry to integrate BIM tools into their project management. These tools offer benefits like speeding up processes, increasing material specification precision, and enabling cost reductions. Utilising BIM-based simulation tools like GBS and One Click LCA for alternative design scenarios can lead to more energy-efficient and sustainable solutions by evaluating multiple design options. Further research into the long-term performance and adaptability of these designs post-construction can enhance understanding of BIM's role in optimising building life cycles. Additionally, exploring BIM collaborative potential may help address issues like project delays and cost overruns. The outcomes from diverse design scenario analyses illuminate BIM capacity to augment energy efficiency, curtail environmental impacts, and foster the development of sustainable and economically viable built environments. Furthermore, this study opens avenues for further exploration into BIM collaborative potential and emphasises the necessity of maintaining data integrity throughout the building lifecycle to fully leverage BIM-LCC integration. These insights not only contribute to the body of knowledge in sustainable construction practices but also provide a strategic framework for future industry applications. This data clearly supports the revised conclusions, emphasising BIM role in enhancing cost-effectiveness and sustainability in residential construction projects.

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Integrating BIMs in Construction and Demolition Waste Management for Circularity Enhancement-A Review

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Abstract. Humanity in our days is fighting with climate change effects and the depletion of natural resources. In this direction, the adoption of sustainable and circular practices is considered vital and in most cases is prescribed by regulations. The construction sector is responsible for massive amounts of energy consumed during the extraction of raw materials, the production of building materials, the construction phase, the operating phase of the buildings, and also during their demolition and end-of-life. The latter one already gathers the scientific community's interest with the efforts being focused on efficient Construction and Demolition Waste (CDW) management solutions. Meanwhile, Building Information Modelling (BIM), as a storage medium of information about all building components, offers various advantages on a building's optimum design and operation, allowing information exchange among all involved stakeholders. Although many studies demonstrate the effectiveness of BIMs in reducing construction waste for new buildings, there is not extensive research on how BIMs can contribute to CDW reduction for an existing building. In this review study, the existing studies addressing BIM integration on CDW management are analyzed, pointing out the advantages that this strategy offers on reducing CDW and managing them efficiently, increasing reuse and recycle rates, and promoting circularity. The main challenges this approach presents, mainly attributed to the difficulty of gathering the required information with the appropriate accuracy about an existing building, are extensively discussed, along with future research needs, necessary for a further enhancement of this technique.

Keywords: Construction and Demolition Waste · CDW · Waste Management · Building Information Modeling · BIM · Circular Economy

1 Introduction

The construction industry is directly related to the needs and dynamics of society development, but its rapid growth is also accompanied by negative consequences. The construction sector is responsible for significant energy consumption during stages such as

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building material production, construction, and building operation, as well as depletion of natural resources and other concerns during end-of-life processes. One of the primary concerns during this phase is Construction and Demolition Waste (CDW). Statistically, within the European Union, CDW represents on average more than 37.5% of the total amount of waste produced [1]. For instance, according to [2], disposal and landfilling of the mineral fraction, which accounts for the largest share of total CDW, is still the predominant form of management in some countries, particularly in Central and Eastern Europe, such as Bulgaria (more than 70%), Slovakia (almost 50%) and others. For Norway, this number varies between 40% of mineral CDW disposed of and almost 20% used for backfilling.

The increasing amount of waste generated during construction and demolition has heightened public concerns about the industry's environmental impact, which raises questions about the use of sustainable practices such as implementing Circular Economy (CE) and focusing on effective CDW management solutions. CE principles require a rethinking of linear approaches to waste management and a paradigm shift. A novel CE concept is based on a business model system that aims to replace the conventional "end-of-life" concept to slow and narrow material flows and close the loop [3]. Implementing these principles leads to preventing resource wastage, prolonging the lifecycle of buildings and their components, and increasing waste recycling, including the CDW. In fact, the need to increase reuse and recycling CDW rates is driven not only by environmental impact considerations but also by the potential economic benefits and conservation of limited resources [4]. As the current rates of reuse and recycling of CDW are lagging behind the growing waste production, the implementation of CE could significantly reduce the landfilling of CDW and eliminate the amount of CDW in general [5].

Designing new buildings and planning for end-of-life scenarios using a combination of CE principles and digital tools such as Building Information Modeling (BIM) modeling helps to reduce future CDW coming from existing buildings and use it more effectively [6]. BIM technology has concentrated the interest of researchers studying CDW management and tens of studies can be detected internationally, with their number constantly increasing. In this study, the most recent research covering the ways BIM modeling can promote CDW effective and sustainable management along with CE practices is recorded and presented. The benefits, but also the challenges accompanying BIM's implementation are gathered, while the various BIM-based tools developed by various researchers are thoroughly examined.

2 BIMs Implementation on CDW Management

CDW production is expected to rapidly increase in the following years, especially in the European Union (EU) where the building stock is old, with a great portion of it dated at the beginning of the 20th century [7]. BIM as a storage medium of multiple and extensive building properties can enhance CDW management and promote CE principles.

2.1 Analysis of BIM Properties

Most countries have established policies and regulations towards a CE, while among them several targeting CDW reduction and recovery. Nevertheless, according to a study conducted in North America and considering the existing regulations in that area, their effectiveness varies among the various building types [8]. Different building characteristics are not properly considered by the existing regulations, preventing optimum results. Meanwhile, the existing CDW tools present limitations, such as they are completely design-detached, and lack interoperability capabilities, while their environment does not promote stakeholders' collaboration [9]. Urban Mining (UM) is indisputably connected to CE practices, with Material Flow Analysis (MFA) being one of its critical processes [10]. Material Intensity Coefficients (MICs) definition is a rather challenging process since their values are related to the geographical area, the local conditions, and the researchers' approach. The aforementioned parameters limit the promotion and effectiveness of CE practices; thus the research interest has focused on BIM technology.

BIM-based CDW management techniques can be implemented even from an early-design stage of a building. Up to 15% extra waste is considered to be produced during the construction stage and is related to construction errors [11]. Nevertheless, BIM modeling can prevent these errors efficiently by eliminating design flaws. This is mainly related to the visualization and the high level of details that a BIM model contains, to which all involved stakeholders have access and can contribute to the optimization of the design phase [12]. According to construction industry experts from the UK, BIM modeling has several advantages when used for CDW management, as it allows the continuous assessment of the CDW amount and the management techniques throughout a building's lifespan, it provides precise data about building's materials, and components and if it is combined with other advanced technologies the whole CDW management process can be further optimized [9]. Other benefits from BIM implementation are the detailed planning and management of the construction materials' delivery and the construction site, the design for deconstruction, the promotion of prefabrication, and the ability to plan and control everything 3D [13, 14].

Despite the benefits BIM modeling offers to CDW management, its actual implementation in the industry is still limited. In fact, according to a study conducted in Australia, less than half of the interviewed construction stakeholders use it in their projects [15]. Several parameters exist that hinder BIM's wider implementation on CDW management. To begin with, the lack of regulatory framework and guidelines covering this field is one of the most deterrent parameters for the involved engineers, followed by the BIM's software inability to exchange data on actual time with other End-of-Lifetime (EoL), CDW and Life Cycle Analysis (LCA) tools, while another parameter is the absence of available and credible Material and Component Banks (MCBs), leading to lack of knowledge about the material properties [12]. A study conducted in the UK revealed that there are five main reasons for the limited BIM implementation, which are the lack of experts in this field, the industry's unwillingness to follow the new practices, the level of responsiveness of business models to these advanced techniques, and the lack of standardization from an early-design stage [16]. What is also pointed out in the various studies existing in this field, is that even if there have been many efforts to include BIM-based CDW management from an early-design stage, there are very limited studies on the technology's implementation in existing buildings [13]. The main reason for this phenomenon is the lack of documentation and drawings for the majority of the existing buildings, which is challenging for the creation of a credible BIM model, so activities like scanning and point cloud creation are necessary for building the model, nevertheless they require expertise, and they are time-consuming [17].

Figure 1 presents, in brief, all the benefits and challenges that BIM-based CDW management has, as they were gathered from the literature and presented analytically in the previous paragraphs.

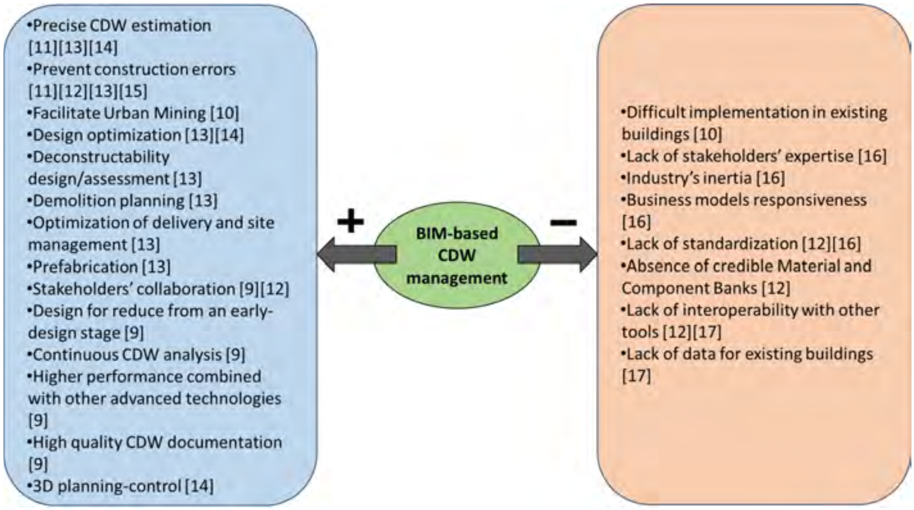

Fig. 1. Benefits and challenges of BIM-based models' implementation in CDW management according to the international literature.

2.2 Developed BIM-Based Tools

Several researchers have developed theoretical and/or practical frameworks to enhance the efficiency of CDW management practices making use of BIM technology. Analytically, a theoretical framework was presented in [18], targeting at reducing the produced CDW throughout a building's lifespan and increasing the reuse and recycling rates. A cost-benefit analysis is also included in it, helping the involved stakeholders determine the optimum CDW management solution. The specific framework can be applied from an early design stage and is suitable also for renovation and demolition processes. Another framework addressing mainly existing buildings was developed in [19], where the building under examination is firstly scanned to build the BIM model, while in a following stage and depending on the treatment applied to each material and component, the demolition and the transportation processes can also be planned. By implementing this framework, reuse and recycling are promoted. In study [20], the researchers developed a framework for building a 3D BIM model for existing buildings, where images must be taken from the internal and the external side of the investigated building, with some overlapping between them. Then the BIM's development is based on the photogrammetric point cloud. After creating the BIM model, the researchers have all the materials and components' properties, so a precise CDW estimation is feasible, and combined with a cost-benefit analysis, the optimum demolition and CDW management planning can be determined.

Material Passports (MPs), as a database storing all the materials of a building and their properties, is an important CE tool. A BIM-based MP's implementation in existing buildings was studied in [21], to assess the materials' recyclability and the environmental impacts they have after the building's demolition. Laser scanning was used by the researchers to create the point cloud and then develop the BIM model of the building, with the materials' quantity and composition defined through demolition acquisition and UM processes. Based on an Austrian database related to new buildings, they calculated for each material the recyclability and environmental impacts. An interesting approach was also elaborated in [22], where the researchers included sustainability assessment indicators in the MP they developed. In more detail, shared parameters related to the indicators were created in Revit and then Dynamo Visual Programming was used to model the indicators so they can be calculated. The indicators that they integrated in the MP are the deconstructability score, the recovery score, and the environmental score. The MP was validated through a case study. Based on BIM models of various buildings, a web-based MCB was developed in [23]. In this database, to where all the involved stakeholders have access, all the information of a building's materials is available and calculations of CDW, reusable and recyclable materials are constantly available. The whole process involves the extraction of a Dynamo script from Revit and using PHP and MYSQL the data can be stored in the MCB.

Many researchers focus on developing BIM plug-ins to extend their models' abilities. For instance, a plug-in calculating the CDW amount produced in every phase of a building's lifespan, according to the architectural, structural and mechanical BIM models, was presented in [24]. The data exported from the plug-in calculation can then be used by an LCA tool to assess the environmental impact. The researchers validated their tool with a case study, and they concluded that using the BIM model to manage CDW from an early design stage can promote design for deconstruction and reduce the CDW production in all stages. A BIM add-in, called WE-BIM Add-in, provides the construction stakeholders the ability to calculate the CDW production (types and quantity) from an early design stage so that solutions for reducing them can be adopted [25]. A BIM plug-in presented in [26] aims at increasing deconstruction and reducing CDW production, by categorizing all the elements of a building to be renovated or demolished and uploading the data in an online shop to which is connected. Based on the customers' demands the elements' dismantling is prioritized, while for the rest elements that received no interest a conventional demolition procedure can be followed. Furthermore, a BIM-based tool targeting effective demolition waste management was developed, which can be implemented from the design stage [27]. The demolition waste amount is calculated from the data provided by the BIM model, its optimum treatment can be defined by making use of Geographic Information System (GIS) technology, and by using an LCA tool the environmental impacts can be also assessed.

Cost optimization in CDW management can be achieved easier through BIM implementation, as the involved stakeholders have a clear view of the whole process even from an early design stage. For instance, in [28], they developed a system where data from the building's BIM model are extracted into the Microsoft Access database, and a detailed CDW calculation is feasible. Then a cost-optimization can be conducted regarding the most convenient companies to be involved in the demolition and transportation processes along with the detailed planning of these procedures. In study [29], the researchers concluded that a BIM-based CDW management adaptation is cost-beneficial, as in the case study they examined the management cost reduced by up to 57% compared to the conventional CDW management practices, with the percentage increasing even more when taking into account the profit from selling reusable and recyclable materials.

Continuing with BIM-based CDW tools, a BIM-based CDW information system was developed based on the 3R principle and a Reversed Logistics (RL) network defines the CDW management procedure, and the environmental costs are calculated through mathematical formulas [30]. Selected Greenhouse Gass Emissions (GHG) can be also evaluated both for recyclable and landfilled waste [31]. Finally, the addition of the time dimension in CDW management is also feasible with BIM modeling. According to a study calculating the potential on-site reuse and off-site recycling for concrete and drywall waste, tons of waste can be avoided due to the ability of 4D BIM to repeat the calculations for every component taking into account the actual construction sequence [32].

Table 1 displays all the aforementioned BIM-based CDW management tools, presenting their type, the tools used for their development, their main target and whether they were applied in a case study.

Table 1. Different types of BIM-based CDW management tools.

Study	Type	Tools used	Main target	Case study
[18]	Framework	-	CDW management	-
[19]	Framework	Building scanning	CDW management	University building, Hong Kong
[20]	Framework	Building images	Demolition and waste management planning	Residential building in Chongqing, China
[21]	BIM-based MP	BIM software, laser scanning	Materials' recyclability & environmental impact	Industrial building, Austria
[22]	MP	Revit	Buildings' sustainability	Residential building in October, Egypt
[23]	Web-based MCB	Revit, PHP, MYSQL	CDW management optimization	Residential building from ECON4SD project

(*continued*)

Table 1. (*continued*)

Study	Type	Tools used	Main target	Case study
[24]	BIM/BIM plug-in	Revit, Athena	CDW calculation and reduction	Commercial building in Montreal, Canada
[25]	BIM add-in	Revit	Construction Waste calculation from an early-design stage	Residential building in Seville, Spain
[26]	BIM plug-in	Revit	Deconstruction and reduce promotion	Office building, Revit's sample
[27]	BIM-based tool	BIM software, GIS, LCA	Estimation & evaluation of demolition waste	Educational building in Huai'an, China
[28]	BIM & cost-optimization system	Revit, Microsoft Access database	CDW management optimization	Revit's sample
[29]	System Dynamic model	BIM software	CDW management optimization	Commercial building in Montreal, Canada
[30]	BIM-based information system	Revit	CDW management optimization	Office building in Chengdu, China
[31]	BIM-based information management system	BIM software	CDW calculation and GHG emissions reduction	Educational building, Pixian, China
[32]	Temporal-based algorithms	BIM software	Concrete and drywall waste reuse and recycle	Two non-residential buildings in Texas, USA

3 Discussion/Conclusions

CDW production and its environmental impacts is a major issue that the construction industry is facing nowadays. CE closed-loop principles promise sustainable and efficient management; however, the current CDW management tools and the way national guidelines and regulations are formed, hinder full CE benefits. In this direction, EU promotes the integration of advanced technologies, like BIM modeling, in CDW practices to optimize their efficiency and achieve sustainability goals. In this review study, BIM-based CDW management properties and tools were presented and categorized briefly.

BIM technology provides the construction stakeholders with lots of benefits. BIM-based CDW management tools have been developed by several researchers and the results they present are satisfying and promising for further performance enhancement. CDW production seems to be reduced as clashes and construction errors can be detected even from an early design stage and eliminated. CDW calculation is also feasible throughout a building's lifespan and detailed planning for all the CDW management stages can reduce costs and time.

Nevertheless, there are still some issues related to BIM technology that are challenging for proper CDW management. Interoperability between existing BIM software and CDW management or LCA or EoL tools is still not feasible, so more complicated and time-consuming solutions need to be implemented to overcome this problem. One of the most important issues on the credibility of the whole BIM-based CDW management relies on the accuracy and the detail of the BIM model. This inserts a level of uncertainty in existing buildings, as in most cases there is not enough documentation and drawings that can provide the necessary data for a proper BIM model development. To overcome this issue, many engineers and designers use statistical and local data, but the level of the model's uncertainty in this case is relatively high. Other practices, like laser scanning and audits, are also adopted, but these techniques require expertise and are also time-consuming. This is the main reason why there is still a very limited number of studies for existing buildings.

To conclude, BIM-based CDW management is undoubtedly the future of CDW management, but there is still a need for further research since the field is in an immature stage.

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Sustainability in the Context of BIM-Enabled Digital Building Permits

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Abstract. The construction industry is one of the most resource-intensive industries and one of the largest contributors to greenhouse gas emissions and waste production. Building information modelling (BIM) can help architects and engineers design more energy-efficient buildings with less waste, contractors build more efficiently with fewer errors, and facility managers operate buildings more sustainably while reducing maintenance costs. In addition to the well-established benefits of using BIM in construction projects, adopting an openBIM workflow can further streamline the permitting process, making it more efficient and transparent. Digital building permits (DBPs) are intended to further improve process efficiency by digitalizing and automating conformity and code compliance checking processes of obtaining building permits. Further, by integrating sustainability concepts, DBPs have the potential to revolutionize city planning and urban development by enabling more sustainable construction practices and reducing the environmental impact. This study explores the relationship between BIM and DBP in the context of sustainability presenting the current ongoing activities and implementation challenges and proposes a series of solutions.

Keywords: Building Information Modelling · openBIM · Digital Building Permit · Sustainability · Digitalization · Urban Development

1 Introduction

According to the International Energy Agency [1], decarbonising the buildings and construction sector is critical to achieving the Paris Agreement commitment. Governments and private companies alike have pledged to achieve a net-zero carbon emissions building sector and have set a goal of mobilizing USD 1 trillion in developing countries by 2030. In addition to the environmental concerns, the energy crisis squeezed budgets as prices soared in 2022. Government interventions moderated the extent to which higher commodity prices fed through to higher household energy bills, nevertheless, there were increases in natural gas, petrol and retail electricity prices in various parts of the world [2]. Through digitalization, the Architecture, Construction, Engineering and Operations industry (AECO) can: i) reduce costs by automating tasks, reducing waste, and improving communication and collaboration; ii) improve the quality of work by

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providing better tools to visualize designs, track progress, and identify and resolve problems early on in the project lifecycle; iii) design and build more sustainable buildings and infrastructure and iv) improve safety on construction sites by providing better tools for hazard identification and risk assessment. In addition to these benefits, digitalization can also attract and retain top talent, with younger generations being increasingly drawn to industries that are using cutting-edge technologies [3]. According to the NBS Digital Construction Report [4] 80% of the AECO companies agree that digitalization is helping to create better buildings and places; 75% agree that it is having a positive impact on environmental sustainability and that it is helping to create a safer built environment. Modern building practices are increasingly defined by three pivotal elements: Digital Building Permits (DBP), Building Information Modelling (BIM), and Sustainability. DBP transitions the permit process from traditional paper-based methods to a streamlined online system, improving efficiency and stakeholder collaboration. BIM transforms design and construction by creating detailed 3D digital models of buildings, promoting better decision-making, communication, and early identification of design conflicts. Sustainability in construction focuses on environmental responsibility and efficient resource use, incorporating eco-friendly materials, renewable energy, waste reduction, and water conservation, thereby improving the built environment's quality. This study aims to merge the dimensions of sustainability, BIM, and DBP. The approach involves a literature review leading to a matrix development. The goal is a nuanced understanding to address challenges and delineate potentials in the integration of BIM, DBP, and sustainability, providing a comprehensive foundation for future studies.

2 Research Methodology

The research methodology was chosen to comprehensively analyse the integration of BIM, DBPs, and sustainability within the construction industry and it is twofold: first, conducting a detailed literature review, and second, developing a matrix to systematically evaluate and integrate the findings. The literature review was divided into three phases: i) establish a baseline understanding of BIM, DBPs, and sustainability; ii) identify challenges in integrating these areas; and iii) explore existing solutions and benefits of this integration. After the review, a matrix based on cluster analysis was created to systematically categorize challenges, potentials, and solutions, focusing on various aspects such as education, standards development, government incentives, collaboration, research, leadership, and technology integration. This methodology was instrumental in providing a comprehensive understanding of the current state and challenges in integrating sustainability with BIM and DBPs. It also helped in proposing structured solutions, thereby contributing to the advancement of sustainable construction practices. The approach enabled a nuanced discussion on the potential for integrating sustainability into BIM-enabled DBPs, setting a foundation for future research and practical applications in the field. Figure 1 presents schematically the research methodology adopted within the paper.

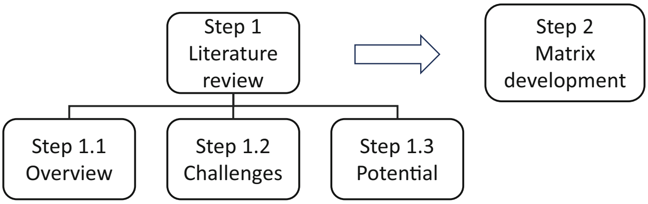

Fig. 1. Methodology Diagram for Sustainability integration in BIM-enabled DBP.

3 General Findings and Basic Overview

Today's building permit issuance is mainly a manual, document-based process with a high dependency on the legal framework and governmental processes. This makes the process extremely complex, prone to errors, non-transparent, and unpredictably lengthy [5]. Model checking based on data extracted from the model is a largely explored area with many software developments since the broad adoption of BIM in construction. To support transparent information transfers, buildingSmart focuses its efforts to develop openBIM [6], a collaborative process that extends the benefits of BIM by improving the interoperability, accessibility, usability, management, and sustainability of digital data. The value of openBIM is significant providing the fact that it promotes a vendor agnostic real-time data visibility and access to digital models throughout a building's lifecycle for different actors. OpenBIM can be seen as a supporting instrument that can be integrated into DBP. BIM maturity level 2 relies heavily on openBIM [7] for visualization, collaboration, data management, and complete data integration in a cloud-based environment.

From the sustainability point of view, to achieve the required emissions reduction for sustainable and resilient buildings given by the UN Environment Programme [8], decision-makers must urgently put in place concrete actions. For this, increased funding is required for public-private research partnerships to accelerate the development, demonstration, and commercialization of innovations. Furthermore, regulations and assessment of emissions need to take a life cycle approach that considers both materials' embodied and operational carbon emissions. Through digitalization and BIM, the IEA Net Zero Emissions can be met by 2050 [9], but all countries need to establish building energy codes with the vision to transition to zero-carbon-ready buildings. This will require more than doubling the annual energy efficiency renovation rates globally, from the current level of less than 1% up to 2.5% by 2030. According to the NBS Sustainable Futures Report 2022 [10], achieving 'net-zero operational carbon' is the most important sustainable project outcome. The use of BIM to get BSA (Building Sustainability Assessment) certification is possible with some adaptations to allow simultaneous analysis and better performance [5].

Translating the traditional permitting process into an automated DBP is not a straightforward process since the analysis of regulation, understanding the workflows within an administration, and creating or translating legal texts into machine-readable are nearly impossible to implement. Still, DPB is in focus for many countries. For example, the authorities from Singapore have required that for new buildings that are more than 5000 m^2 digital BIM models to be submitted since 2015. In Korea, BIM has been compulsory for all public sector projects since 2016. In Norway, BIM submission was introduced in 2010 for all public sector projects, while in UK, BIM level 2 models have been required for all public projects since 2016. To create a BIM-based building permit checking service within the Building Registry for the Estonian Government, the BIM-based Building Permit Process project team [13] has developed a comprehensive list of recommendations, best practices and lessons learned. Dubai Municipality has started a project aimed to design and implement a roadmap for BIM to design unified BIM standards with Geographic Information System (GIS) integration, to enable authorities to apply rule-based automatic code compliance checking and develop specialized tools to improve the process of issuing building permits. The first phase of the BIM standard for building permit has already been published, and the second phase is planned for 2024 [14]. Finland is planning to accept Industry Foundation Classes (IFC) for archiving by 2025. The archival materials include letters that have been arranged into groups according to content (classification code) [15].

One of the major adoption challenges is the organizational resistance, that often originates from a lack of understanding of the benefits of BIM, concerns about its implementation costs, and fears of job displacement [16]. To address these concerns, future-oriented organizations usually focus on i) education to provide comprehensive understating to employees on the principles and benefits of BIM, showcasing the application of BIM in real-world projects [6, 18]: ii) defining clear goals and measurable objectives in alignment with organization's global business objectives, while establishing a BIM implementation plan with clear steps, resources, and timeline for adoption; iii) employing change management strategies to address concerns about job displacement and workflow disruptions, by providing training and upskilling opportunities for employees to better adapt to BIM-based workflows. In the same time, fostering a culture of collaboration and open communication to address resistance and concerns. Another significant barrier to BIM adoption is the lack of skilled professionals. To address this challenge, organizations usually i) invest in training or implement internal training programs for BIM standards, processes, and software; alternatively, they ii) partner up with universities or professional associations that offer BIM-related courses and certifications and iii) foster a culture of learning within the organization.

On a technical level, the adoption of BIM requires a robust software infrastructure that supports the creation, management, and exchange of information. To streamline BIM adoption, companies have to i) carefully evaluate and select BIM software platforms that align with the organization's project types, workflows, and budget and consider functionality, interoperability, and vendor support [19]; ii) establish clear data management standards to follow, define data naming conventions, file formats, and metadata requirements; iii) invest in adequate hardware and IT infrastructure that supports BIM software and data management, ensure the bandwidth and storage capacity that can handle the demands of BIM-based projects.

4 Challenges of Integrating Sustainability in BIM-Enabled DBP

In a familiar work environment where the intricacies of a project are not appropriately interconnected, grasping the broader significance of change concerning digitalization, automation, BIM integration, and sustainability becomes challenging [20, 21]. As building projects advance, it is crucial to embrace appropriately scaled workflows. A fundamental barrier to the implementation of BIM use cases for DBP is the lack of understanding that most of the projects are facing. In most cases, BIM is considered as a methodology with a theoretical basis, but it lacks an understanding of the practical parameters [22–26]. Proficiency in this matter can be acquired through practical, hands-on experience. In terms of technical integration of BIM methodologies, there is a need for primary solution support, rather than conscientious theoretical knowledge. There are several challenges in adopting and implementing advanced technologies which serve sustainability, and this requires specialized knowledge and expertise [27–30]. Local authorities need to be aligned with the technical aspects of sustainable design. To achieve this, adequate technological infrastructure is necessary to support the DBP implementation. The authorities need to invest in secure and reliable systems, which can handle the complexity of data processing. Stakeholders might face challenges in adapting new sustainable practices in their work due to resistance to change [30, 31]. To mitigate this, the traditional working methods need to be challenged by user-friendly sustainable design practices. Meanwhile, reliable data on the environmental impact of construction practices as well as the traditional materials, are lacking or are inconsistent and, for a consistent DBP process, accurate information and assessments are needed. A possible solution would be sustainable and BIM-based projects, with a clear objective to continuously leverage and consolidate best practices and lessons learned. Additionally, there is also a strong need for investing in training, such as the development of training programs for BIM standards, processes, and software platforms. Although the potential awareness of sustainability integration into BIM-enabled DBP is increasing, the process is extremely slow. The UK and numerous European countries such as Denmark, Netherlands, Belgium, Portugal, and Slovenia are fervently urging the need for integration of BIM use in public building projects. Additionally, a proposed European project which took place in 2018 included different European countries for mandatory adoption of BIM integration in further new public building projects as regulations [33]. There were similar approaches at the municipality level, where local authorities are adopting decisions to use BIM in large construction projects. In most cases, the transition from paper-based documents to digital files, even if technologically feasible, presents legal issues. There is also a lack of universal standards for electronic signatures that presents a complex adoption process due to the interoperability of different systems and platforms.

Challenges persist in the case of sustainable policies with many countries that are lacking developed frameworks. Current building codes and regulations fail to meet incentivized sustainable practices [34]. Consequently, there is a need to update the existing regulations in the municipalities, adapting them to sustainable methods, to encourage and reward sustainable design without supporting bureaucratic barriers. To support this, various standards are emerging, including well-established ones like BREEAM, widely used in the UK, and LEED, a prevalent green building rating system based on certificates. On a local regulatory level, there is still a need for the definition and standardisation of sustainability criteria. Additionally, the obligatory consideration of sustainable BIM usage at the national level is currently missing, but it could be imposed through regulations. The changes in the regulations can be very difficult to take by the permit authorities, and the complexity of integrated sustainable solutions in building permits together with BIM adoption would be a lot to take for physical work. On this line, there is a strong need for cross-country cooperation to facilitate a smoother integration, allowing nations to learn from each other through shared experiences. Merging BIM adoption and sustainable standard solutions, in a well-defined DBP would serve as a comprehensive solution [35]. Sustainable implementation costs into the DBP can be excessive and may include software acquisition, hardware upgrades and training [36]. Simultaneously, the process can get excessively intricate. A high input is required from the administrative part of the public sector, which should offer continuous support for the integration of sustainability in a BIM-based DBP. This is why it is necessary to approach sustainable issues on a national and international level, rather than local [37]. Additionally, the integration of new systems into the existing ones can be very challenging, in particular, the existing databases, and GIS [19]. A potential solution for this would be a modular approach, which could ensure backward compatibility with existing systems. Also, a phase-based adoption would reduce implementation costs. The collaboration for digitalization between the authority and the private sector would reduce the need for extensive physical infrastructure.

As the adoption of sustainable materials can be more expensive than traditional building materials, there is a need to demonstrate the long-term economic benefits of sustainable practices. Addressing these challenges requires a collaborative effort between multiple industries, simultaneously implementing supportive sustainable policies and practices, and providing educational resources [38, 39] for the integration of sustainability and BIM into the DBP system [40].

5 Potential BIM Benefits for DBPs Sustainability Assessment

Use of electronic documents for the building permit process provides opportunities for cost savings, elimination of archiving costs, improved workflow efficiency, reduced shredding costs and fewer trips by the contractor's representative to the building department [41]. Transitioning from paper documents to electronic documents is not easy, quick nor cheap. It is, however, efficient and will shorten the turn-around time for processing most permits. Furthermore, using a digital system can create additional benefits like i) use of digital signatures; ii) documents transmitted online that can be submitted and collected 24/7, iii) documents stored on a network server, allowing controlled access by authorized individuals. Furthermore, according to Local Authority Services for Ontario municipalities [42], implementing a DBP process allows municipalities to issue permits 80% faster than paper-based systems and allows building inspectors to leverage technology (e.g., tablet, phone, or laptop) to complete reports in the field, upload photos, and schedule building inspections online. A study conducted on the topic of Digital Twins (DT) [43] described them as a BIM use case for Smart City planning (in Vienna).

As a starting point, BIM model, with geometry and metadata, is submitted for approval, enabling automated checks for building code compliance. Also, a Design/Concept Phase, DT enhances citizen involvement. Post-construction, the updated model aids in project change assessment by building authorities. By federating these DT, an urban DT (UDT) can be created, which is a virtual replica of an entire city. The UDT can be used to simulate and optimize various aspects of city development, such as transportation, energy consumption, and waste management, to support sustainable development [44] and can also be used to monitor the city in real-time, enabling city officials to respond quickly to emergencies and other events [45]. The World Economic Forum [46] has launched a three-year initiative to make DT technology accessible to the public and jointly shape the future of DT city development.

6 Proposed Solutions and Concluding Remarks

Table 1 outlines the general solutions, challenges, and potentials, and proposes a series of specific solutions for integrating sustainability with BIM and DBP.

It is designed to provide a holistic view of the aspects related to BIM in the context of DBP with a focus on long-term sustainability and is based on a thorough literature review and a cluster analysis to ensure that its content is reliable and relevant.

The objective of this paper was to synthesize the concepts of sustainability in the context of BIM-enabled DBP, and further to categorize and propose specific solutions and potential research directions. This was achieved through a comprehensive literature review and concluded with the development of a matrix based on a cluster analysis that presents potential solutions for integrating these three concepts. The matrix can be used by organizations, authorities, and the scientific community to define a roadmap and help them navigate the challenges of BIM adoption and harness its benefits as it provides valuable insights into the intricacies of the process, enabling communities and organizations to more effectively navigate the challenges of BIM for the specific use case of DBP towards sustainability. It also emphasizes the role of BIM in promoting sustainability, thereby contributing to a more sustainable and efficient construction industry with the main benefits of improving efficiency, reducing costs, and enhancing the overall quality of construction projects. Future studies can build upon this research to further explore and validate the solutions proposed in the matrix, and to delve deeper into the integration of sustainability with BIM and DBP in different sectors and domains.

Table 1. Sustainable BIM-enabled DBP overview.

Cluster	Challenges	Potentials	Potential solutions
Education and training	Lack of understanding of BIM benefits, scarcity of skilled professionals [22–26]	Enhancing educational performance, while stimulating innovation [38, 39]	Comprehensive education programs, training development for BIM tools and standards, and DBP processes [26]
Development of standards and guide	Determining appropriate BIM strategies, standardising information exchange [34]	Integration of LCA in Building Sustainability Assessment, improving green assessment [28]	Evaluation and selection of BIM solutions, ensure clear data standards, investment in adequate IT hardware [24]
Government incentives	Inadequate BIM competence, limited contribution of BIM since its introduction [26]	Formal integration with Building Performance Evaluation, and Post Occupancy feedback [28]	Government incentives for sustainable business practices [23]
Collaboration and Communication	Organizational resistance, concerns about job displacement [24–26]	Fostering a culture of collaboration and open communication [24, 34]	Employing change management strategies, establishing BIM communities of practice [24, 34]
Research and Development	Lack of research and BIM implementation [28]	Enhancing efficiency of building projects, reducing energy and resources consumption [23, 28]	Conducting comprehensive literature reviews, carrying out empirical investigations, developing strategies to alleviate barriers [28]
Leadership	Lack of buy-in, inadequate resources and training, unclear goals and expectations [28]	Enhancing project delivery culture, generating more innovative ideas and job opportunities [23]	Creating buy-in and support, investing in resources and training, setting clear goals and expectations, leading by example [28]
Integration with Other Technologies	Determining appropriate integration strategies [25, 26]	Monitoring of technical installations, energy consumption tracking, improvement of buildings performance [19]	Integration of BIM with other innovative technologies such as aerial photogrammetry, handheld scanning tools, and automation tools [19]

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Digital Technologies and Material Passports for Circularity in Buildings: An In-Depth Analysis of Current Practices and Emerging Trends

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Abstract. The construction industry is undergoing a significant transformation driven by digitalization and an unwavering commitment to implementing circular economy (CE) principles and sustainability into its core practices. Emerging digital technologies (DTs), such as Material Passports (MPs), Building Information Modelling (BIM) Artificial Intelligence (AI) and Scanning technologies, Blockchain technology (BCT), the Internet of Things (IoT) stand out as pivotal tools capable of expediting the transition towards CE implementation in buildings. This study highlights the significant potential of six DTs to support CE application throughout the building lifecycle. Furthermore, it delves into the potential synergies among these diverse DTs, highlighting the additional benefits that collaboration can bring across different lifecycle stages of a building project. Particular emphasis is placed on the integration of MPs with other DTs, showing promise in assessing resource availability, volumes, and flows. This integration optimizes waste reduction and recycling plans, contributing to more precise selective and smart deconstruction planning. The combined use of DTs offers substantial benefits to stakeholders, enabling them to make informed decisions regarding maintenance and understand the current quality of specific materials. Through these means, the study aims to provide a comprehensive overview of the array of DTs propelling circular building practices. It also explores emerging trends in this dynamic field, scrutinizing the effectiveness of adopting these technologies throughout the building life cycle stages, and anticipating potential challenges these technologies may face.

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1 Introduction

In a technological world that is evolving rapidly, digital integration has become an integral part of our lives. This transformation extends to the construction sector, where digitalization plays a crucial role in changing the existing approach to work. In recent years, the Industry 4.0 paradigm - a new revolutionary approach to the construction process, also known as Construction 4.0, driven by the integration of digital technologies (DTs), has been actively developing. Digital revolution opens up new possibilities from the early design phase to the end of the building lifecycle [1].

The integration of DTs is also becoming a powerful driver for the CE concept, which aims to minimize waste, reduce the use of virgin materials, and optimize the value of products through reuse and prolonged life [2, 3]. According to the CE Action plan, modern approaches based on the use of DTs such as the Internet of Things (IoT), Blockchain Technology (BCT), and Artificial Intelligence (AI) will accelerate the process of circularity in construction and the dematerialization of the economy. This strategic plan places a strong emphasis on the integration of digitalization strategies. Thus, it is assumed that DTs have significant potential to support CE in architecture, engineering, and construction [4].

Digitalization provides a wealth of data that can be systematically analyzed to identify opportunities for the collection, reuse, recycling, and effective management of End-of-Life (EoL) for building elements. Furthermore, it facilitates real-time insights into product availability based on element location, thereby optimizing resource management and enhancing the overall efficiency of the design and construction process. Various digital tools and technologies play a critical role in increasing the transparency of the supply chain, allowing for the tracing of the origin and life cycle of building materials.

In light of the evolving roles of DTs in the construction industry, extensive research has been conducted to explore various aspects such as trends, barriers, and methodologies supporting this research direction. Despite the progress made, the accelerated development of DTs necessitates ongoing research to address emerging issues and opportunities. Particularly noteworthy is the rapid advancement of AI and its ability to learn quickly. Given all, predicting the possible trajectory of digitalization within the CE context is now a highly pertinent task.

This study aims to provide a comprehensive overview of current practices related to DTs and their integration into CE practices, emphasizing their applications, opportunities, and limitations and exploring recent trends in the evolving landscape of DTs in the architecture, engineering, and construction (AEC) industry.

2 Materials and Methods

This research endeavors to comprehensively examine the prevalent DTs and tools employed in the building sector, with a primary focus on facilitating the transition to a CE. The objective is to delineate the roles and synergies of these tools throughout various stages of a building's life cycle, emphasizing their interactions with digital MPs. To achieve this goal, the current study critically reviews the state of the art, spotlighting six widely utilized DTs in the building domain: 1) Building Information Modeling (BIM) and Digital Twins, 2) Internet of Things (IoT), 3) Blockchain Technology (BCT), 4) Scanning Technologies, 5) Artificial Intelligence (AI), and 6) Material Passports (MPs). Subsequently, the study examines the interactions of these analyzed DTs with MPs, addressing the potential integration and the benefits they bring in supporting CE strategies within the processes and practices of building construction. Following this, the study maps these tools across the six pivotal life cycle stages of a building: 1) conception, 2) design, 3) procurement, 4) construction, 5) operation and maintenance, and 6) deconstruction. This mapping exercise serves the purpose of discerning the roles and collaborative synergies among the tools, thereby supporting the realization of digital and circularity objectives specific to each life cycle stage. The mapping is complemented by a comprehensive discussion, elucidating the main challenges and barriers that hinder the full exploitation of digitalization in the AEC. Furthermore, the discussion highlights future perspectives and research opportunities aimed at addressing the identified gaps.

3 Digital Technologies in the Construction Industry

3.1 BIM and Digital Twins

Building Information Modeling (BIM) stands out as the foremost digital tool extensively employed to support the design, construction, and operation of buildings, as well as to facilitate EoL processes [5]. It provides a precise digital representation of building components. Using BIM for effective pre-demolition audits can facilitate and ensure the assessment of the potential to recover, reuse, and recycle material flows [6].

The application of BIM during the demolition process helps monitor the overall condition and performance of the components, as well as the intended recommendations for the demolition stage [7]. For enhanced circularity at the deconstruction, BIM is utilized to assess current conditions, identify components for possible reuse, and conduct a 4D deconstruction simulation integrated with a schedule and a 3D model [8]. Previous studies have emphasized a positive characteristic of BIM - its significant role in improving collaboration and facilitating information sharing among the various stakeholders involved in construction projects.

Digital Twins (DTw) surpass BIM by incorporating live data from the actual operation of a structure, enabling continuous monitoring, analysis, and optimization. A DTw serves as a virtual model accurately representing the geometry, structure, and physical attributes of a real-world product or building. Operating as a sophisticated 3D digital replica, it seamlessly integrates the realms of cyber and physical spaces, finding applications in diverse areas such as product design and production planning. In the context of the built environment, during the operational stages, DTw facilitate the monitoring of energy management, indoor comfort, and safety. Notably, within the framework of circularity, the capabilities of DTw can be further harnessed by generating unique identifications for individual components, commonly referred to as Material Passports (MPs). This will be covered in subsequent sections.

Numerous researchers invest considerable effort in developing Digital Building Logbooks (DBLs) using BIM modeling. However, they encounter challenges in achieving a consistent interconnection between the two. Among the different approaches, the one most used is the International Foundation Class (IFC) file format, although other solutions, such as the Ecodomus software developed by Siemens, also exist. This field is certainly under development, as all of existing approaches present both advantages and disadvantages, with none of them being absolutely suitable [9].

3.2 The Internet of Things (IoT)

The Internet of Things (IoT) is characterized as a networked system comprising sensors and actuators seamlessly integrated with a computing infrastructure. Its primary function is to facilitate the monitoring and management of the health and activities of interconnected objects and machines. This technological framework establishes internet connectivity among sensor-equipped devices, thereby enabling autonomous data collection and analysis [10].

Through the autonomous collection and analysis of data, IoT plays a pivotal role in reducing waste, losses, and expenses, while simultaneously enhancing the tracking and traceability of materials across the supply chain [11]. Consequently, this technology aligns with and supports the implementation of CE principles [12].

3.3 Blockchain Technology (BCT)

Blockchain Technology (BCT) serves as a geographically dispersed and shared database. It functions within a peer-to-peer network, employing a consensus mechanism to uphold the integrity and accuracy of data, which is aggregated into a "chain." This allows for replication across computer nodes. BCT plays a key role in managing information networks, particularly in supply chain management [14].

In the AEC, BCT is increasingly employed to support the tracking of the entire supply chain, including the origins of materials and components. It proves for data analysis, facilitating the potential reuse of information. The technology enables efficient traceability and supports secure, decentralized data exchange between suppliers and contractors. Consequently, BCT is evolving into an indispensable tool for construction companies, particularly during the stages of building construction and materials supply chain [13]. From a product perspective, BCT holds substantial promise in various phases of the product life cycle, ensuring control and quality [14].

3.4 Scanning Technologies

Scanning technologies (ST), known as laser scanning or LiDAR, determine distances to points around a laser scanner, generating local coordinates cross-referenced with geographic coordinates. Predominantly used in the AEC for inspection, monitoring, and 3D reconstruction [15], these technologies contribute significantly to circularity by creating BIMs, CIMs, and MPs. These models, enriched with valuable information, support local governance, smart city initiatives, and CE efforts. Also, ST play a role in reconstructing building facades for energy-based simulations in retrofitting existing structures [16].

ST provides information about geometry and surface materials. For the implementation of CE practices such as preservation, reuse, and recycling, detailed information on the material composition of building elements is crucial, surpassing surface materials. To identify material types within walls and slabs, Ground Penetrating Radar (GPR) was employed in a study to generate MPs for a building [17]. GPR serves as a near-surface geophysical tool for non-destructive characterization of subsurface targets by detecting changes in the electromagnetic properties of materials [18].

3.5 Artificial Intelligence and Robot Learning

Artificial Intelligence (AI) is a key technology driving the transition to a CE, offering three main opportunities: (1) Circular product, material, and component design; (2) Circular business model operations; and (3) Infrastructure optimization for the circular flow of materials and products. In the product development life cycle, AI plays a crucial role in analyzing and improving processes by efficiently handling large datasets and saving time through high-performance computing. In the AEC, AI applications, such as safety measures, structural health monitoring, risk detection, activity recognition, energy demand modeling, cost prediction, computer vision, and intelligent optimization, present significant opportunities [19]. The utilization of AI can lead to significant advancements, one of which is the implementation of MPs. Moreover, when combined with complementary technologies, such as sensors and IoT for smart monitoring, AI not only streamlines the automation of building systems management to improve thermal comfort and optimize energy consumption but also actively participates in shaping the maintenance plan of the building by suggesting preventive actions before potential failures, yet not prematurely [20]. It contributes to CE principles by maximizing the utilization of system components.

A significant potential of application AI and Robot-learning technologies arises at the end of the life cycle of a building. Nežerka et al. [21] harnessed these technologies to develop a machine-learning procedure for recognizing and classifying fragments of Construction and Demolition Waste (CDW). This innovation facilitates the deconstruction process, making it more efficient and streamlined.

3.6 Material Passports (MPs)

Material Passports (MPs) are defined as a comprehensive dataset designed to serve as a guiding source for the analysis of circularity of building products. They play a pivotal role in facilitating decision-making processes related to the recovery, recycling, and reuse of materials and products, as well as all essential information throughout their entire life cycle, promoting optimal use and smart practices [22]. MPs can take the form of a digital presentation on an online platform linked to a database or a manual record of materials. These records encompass important details such as composition, impacts, and supply chain information. By serving as a universal tool, MPs contribute to optimizing the design and product use in the early stages of a building's life cycle. They also aid in evaluating potential changes during the operational phase and addressing considerations at the end of the life cycle. The use of tools like MPs promotes circularity and minimizes waste in construction practices.

4 Integration of Material Passports Within Digital Technologies

From a CE perspective, technologies and tools such as BIM, AI, BCT, IoT and MPs represent innovative solutions that play a pivotal role in facilitating the twin transition towards both green and digital initiatives. These DTs excel in supporting efficient and effective decision-making processes, especially concerning the optimal use and management of resources and energy across the various lifecycle stages of buildings. To fully harness the potential of these technological advancements, it is strongly recommended to employ a collaborative approach. This collaborative effort can expand and complement the capabilities of each technology, delivering even greater benefits for creating sustainable and circular buildings and built environment, overcoming existing and potential barriers to implementation. In this context, this section will focus specifically on exploring the synergies between MPs and other DTs, recognizing their interdependence and potential to drive advancements in the field of CE in construction.

The integration of MPs into BIM models represents a current and promising research area that is attracting increasing interest among researchers. Many studies on the integration of MPs in BIM can be found in the literature, covering new and existing buildings. An illustrative example of such synergies is the development of BIM-based MPs for conducting environmental impact assessments and evaluating the recycling potential of building materials [23]. Several online platforms now automate the creation of MPs based on an IFC file using BIM models. This automation greatly facilitates the calculation of the circularity indicator for the construction, use, and EoL phases [24].

Similarly, MPs, when coupled with Digital twins, play a pivotal role in providing crucial information about the materials incorporated in a structure. Beyond preserving manufacturing histories and inspection records, MPs can be instrumental in estimating the remaining useful life of components. This information, in turn, guides decisions related to component recyclability and reusability [25]. The integration of Digital Twins and MPs enables predictive maintenance, thereby extending the lifespan of building elements and promoting the reuse of materials and components during the EoL stage.

However, developing a BIM-based MP for an existing building poses a significant challenge attributed to the difficulty in obtaining essential material properties due to the absence of available data. For most of the old buildings, there is a notable lack of drawings or pertinent information. Furthermore, even in instances where drawings or other documents are present, their reliability is compromised, given the potential for inconsistencies or alterations in the material elements due to renovations. To avoid such misinterpretations during the development of MPs, techniques such as laser scanning, GPR techniques, and expert-conducted autopsies are used [17].

Numerous studies have delved into the utilization of IoT for generating digital MPs. The collaboration of IoT and MPs establishes a streamlined information collection process characterized by a multidirectional flow of information. This is attributable to the continuous capture and real-time storage of data facilitated by IoT technologies [26]. In addition, a Blockchain-based application can ensure the protection of valuable information and its security against attacks [13]. Dounas [27] showed how BCT can expand the use of MP passports and bring benefits. For example, it is mentioned the possibility of integrating BCT with existing tools, such as BIM and MP.

AI can identify and categorize materials, track their origin, assess their environmental impact, and predict their future performance [28]. These functionalities facilitate data collection and extraction from various resources, data integration, and categorization into structured databases for digital MPs. Lastly, AI aids in the analysis of large and complex datasets, identifying material properties, certification, performance, and standards compliance. Hence, the integration of AI for MPs empowers construction professionals to make informed decisions regarding material reuse, recycling, and disposal, leading to reduced waste and improved resource efficiency [29].

5 Potential of Digital Technologies and Barriers' Discussion

The key prerequisites for a successful implementation process include the establishment of a unified taxonomy grounded in common standards. An illustrative instance of this imperative is the proposed "Standard of Sustainability of construction works - Data quality for environmental assessment of products and construction work - Selection and use of data." This standard, slated to replace CEN/TR 15941[30], underscores the necessity for a shared comprehension of an index encompassing building materials and elements. This index would consider factors such as origin, distance to the site, storage capability and aspects of reusability. A pivotal reference for promoting circularity within the AEC is the emerging Standard EN 17680 [31]. This standard outlines a systematic approach for assessing the sustainability of buildings, using a life cycle perspective. Meanwhile, ISO 37101:2016 [32] has been directed towards MPs to evaluate their performance. However, the assessment remains at general level, lacking a distinct metric for the indexing of materials.

The linchpin for the broader adoption of DTs lies in the establishment of a common taxonomy rooted in a coherent and market-wide adopted assessment framework. AI can be a useful tool to support or even initiate this taxonomy.

Taxonomy with its individual components in digital technology, plays a critical role in overcoming numerous obstacles in utilization. In the case of MP use, AI proves invaluable in organizing information, creating large databases of material data sheets, and highlighting issues related to predictive material usage [29]. Technologies such as IoT and BCT can effectively address diverse system challenges, resolving issues related to collecting and securely transferring information from BIM models and Digital Twins to MPs [13]. This extends to the management side, ensuring transparency in payment, documentation, and collaboration among stakeholders.

Upon analyzing existing studies and practices, it becomes evident that the greatest application of the DTs presented in this paper lies in the Operational and Deconstruction stages of building projects (see Fig. 1). Each tool finds its application in these stages, with a notable emerging trend in EoL material recognition of by AI during deconstruction processes. While BIM and MPs are commonly used in the initial stages of construction, the inclusion of AI for design predictions is a recent development. This suggests that other practices have yet to find active application there in these early project stages.

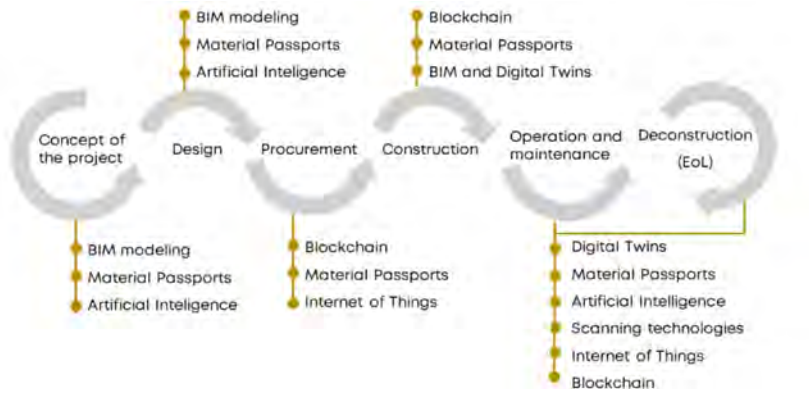

Fig. 1. Digital technologies mapping across various phases of the building life cycle.

The potential of this work can be further realized and extended by incorporating additional tools and DTs such as Big Data, Robotics, and GIS. A synergistic combination of different technologies like MPs, GIS, and AI-scanning can facilitate the creation of comprehensive Material cadasters, scalable to the level of neighborhoods, districts, or even cities.

6 Conclusions

The realization of a complete transition to digitalization within the construction industry is no longer an unrealistic goal. The key prerequisites for a successful transformation include the establishment of a unified taxonomy and a shared understanding of an index encompassing building materials and elements. This index should consider factors such as their origin, distance to the site, storage capacity, and aspects of reusability.

The present study focused on the six most utilized DTs: BIM and Digital twins, IoT, BCT, AI, and ST along with digital MPs. These DTs are assumed to play a pivotal role in expediting the integration of CE practices into construction methodologies on a permanent basis. The findings of this study underscore the paramount significance of the explored topic, emphasizing the imperative need for continued efforts in leveraging DTs to foster sustainable and circular practices, particularly in the end-of-life phases within the construction industry. The positive impact of circularity practices, facilitated by digitalization, extends beyond just enhancing the level of processing, data handling, and categorization through MPs. A more comprehensive integration of DTs throughout all phases of building lifecycle compensates for shortcomings such as information gaps, protection, and transparency, improves decision-making processes and communication among stakeholders while significantly expanding information coverage. The synergies achieved by combining these technologies undoubtedly accelerate their development.

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Digital Technologies for Inventory and Supply Chain Management in Circular Economy: A Review Study on Construction Industry

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Abstract. The characteristics of supply chains in the construction industry give rise to several information and collaboration system needs, such as system affordability and adaptability. The presence of several companies from a variety of industries in supply chains for the construction industry sets them apart. Information sharing and system integration therefore require cooperation and trust. In the manufacturing industry, a lot of efforts are being made to create tools, technologies, and strategies that would allow supply chain actors to communicate with one another and work together. However, it is more challenging to establish a solid environment for inventory and data management in the construction industry. The Internet and information technology are now being used in the construction industry to strengthen cross-organizational relationships. The employment of these tools in this industry is occasionally hampered by limitations like security worries, a lack of managerial commitment, high costs, and deployment rigidity. Additionally, a dynamic configuration of supply chains is required to integrate with more adaptable business models, increase internationalization, and enhance coordination. For this reason, this study primarily explores the inventory and supply chain tools currently in use in the construction industry and evaluates their functionality from a business and consumer perspective. Other areas of study are based on either inventory management for circular buildings or cross-organizational cooperation, and they include secure data storage, information exchange among stakeholders, and their modification. In the end, it aims to emphasize the key problems with data and inventory management in the construction industry, as well as inform about the potential technology solutions to make a guidance of academic and industry specialists within this study.

Keywords: Circular Economy · Construction Industry · Digitalization · Inventory Management · Supply Chain Management

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1 Introduction

Digitalization can be defined as the spread of digital technologies. Research opportunities in the fields of supply chain management and inventory management are greatly expanded by the digitalization of intra and inter-organizational processes [1]. Due to the globalization and cross-border penetration of the current industrial markets, the growth of the business world has resulted in increased market competition. To thrive and preserve a long-term competitive edge in this worldwide marketplace, companies must simultaneously recognize new digital technologies that can be leveraged to create fresh business concepts. The competitive nature of today's market has compelled organizations to implement advanced manufacturing technologies such as rapid prototyping, 3D printing, and the Internet of Things (IoT) for information and analysis [2].

As an alternative to the conventional linear model, the circular economy (CE) is thought to be the most effective way to address the sustainability issues that contemporary society is confronting. CE develops social, economic, and environmental capital through three guiding principles: regenerating natural systems, minimizing waste and pollution, and maintaining product and material use. These principles are supported by the shift to renewable energy sources [3]. Policymaking and public awareness regarding the enhancement of circularity in the economic system are raised by the macro- and meso-level applications of CE. Business firms should proactively implement the circular system in their operations due to the potential synergy of economic, environmental, and social performance through CE, even though they are under increasing pressure from such top-down CE implementations worldwide [4]. From a technical cycle standpoint, the most effective way to achieve true restoration is through circular supply chain operations, such as waste management.

"Digitalization" is one of the most popular topics in the Supply Chain Management (SCM) research field because it has the strongest correlation with "circular economy" when these two terms are used together in the same article [5]. Due to the scarcity of human labor during the COVID-19 pandemic, digitalization has emerged as a necessary trend in circular supply chain management. As we enter the digital era and become a crucial economic pillar, the construction industry has also started to actively support digital transformation, viewing the digital supply chain as a breakthrough that will help to advance the transformation and supply chain upgradation of bilateral customers [6, 7]. Furthermore, digital platforms guarantee sincerity and offer safe verification of the flow of information and logistics within a supply chain network [8]. However, construction companies were not making the best use of their resources, and this could have contributed to a decline in productivity in addition to ineffective management, material management is one of the main concerns in this industry. Therefore, this study mainly aims to investigate the functions of inventory and supply chain tools that are currently used in the construction industry. The study's other goals are to discuss potential technological solutions that guide the knowledge of both academic and industrial experts, store data securely, and facilitate information sharing among stakeholders.

2 Inventory and Supply Chain Management in the Construction Industry

In the construction industry, the term “inventory” refers to the supplies or parts that the contractors have on hand to ensure that the work goes smoothly [9]. Especially, materials tracking has drawn a lot of attention as inventory management has grown in significance. To ensure that construction projects can be completed following the availability of resources, it is crucial to be able to track each building material and its supply chain networks. For this reason, this section investigates the current inventory and supply chain management systematics in the construction field and presents the digital technology-integrated practices of these systems.

2.1 Characteristics of Inventory and Supply Chain Management Systems in the Construction Industry

The construction industry has witnessed the introduction of multiple inventory and supply chain management (SCM) programs since the late 1980s. For the supply chain to operate well, inventory management is one of the crucial components that call for cooperative effort from a variety of stakeholders [10–12]. Numerous studies have been conducted to examine the management of the construction supply chain (CSC) from various angles, including information flow, subcontractor management, intelligent agent-based coordination, value stream analysis, integration, decision support system and optimization tool, and simulation platform [10].

Authorities have implemented environmental restrictions to mitigate the adverse consequences of CSC activities, owing to the construction industry’s negative environmental impacts (CSC). The effects of construction operations on the environment and society are a major source of concern [12]. According to Vrijhoef and Koskela (2000), depending on whether the supply chain, the building site, or both are the main emphasis, there are four main functions that SCM plays in the construction industry. Potentially, the effects of supply chain activities on-site will take precedence. The intention is to shorten the time spent on site and lower costs. To prevent disruptions to the workflow, the main concern in this instance is to guarantee consistent labor and material flows to the site. By concentrating just on the connection between the website and direct providers, this can be accomplished. Second, to cut costs, particularly those associated with inventory, lead times, and logistics, the supply chain itself may be the main emphasis. Suppliers of components and materials may also take up this emphasis. Thirdly, shifting operations from the site to earlier phases of the supply chain can be the main emphasis. Once more, cutting down on the overall expenses and time is the aim. This emphasis could be started by contractors or suppliers. Fourthly, supply chain optimization, site production, and integrated management may be the main areas of emphasis. Site production is thus included in the SCM. This focus may be started by contractors, suppliers, or clients.

Relevant for this industry to become circular is the process of reuse of already used building material that comes from the end-of-life cycle of objects in use. In this context, the remodeling and demolition process (ÖNORM B 3151) is to be organized in a structured way. The waterfall model as of today contains 5 steps as follows:

1. Avoid waste material by maximizing the reuse of buildings or building elements.
2. If there is no direct reuse possible, prepare usable building elements with cleaning and testing for their reuse and store them appropriately.
3. If the reuse is not possible, then the demolition elements and materials should be separated to their original destination material and brought into a recycling process such as glass -or wood recycling.
4. Only in the case of no appropriate recycling of the elements or material composites, a sustainable and economic destination can be the deposition at a site, where there is a requirement for landfill or the waste material has enough thermal quality to burn the material, with the demand, that this measure is without any negative impact to air quality and similar.
5. Only if there is no possibility for any of the previous mentioned steps, there is the last option of putting the waste material under fully controlled conditions into a depot of waste material in an assigned area.

3 Digital Technologies in Inventory and Supply Chain Management Systems

In the contemporary worldwide corporate climate, the integration of digital technologies into production has grown in significance. The application of developing digital technologies, such as the Internet of Things (IoT), big data analytics (BDA), and artificial intelligence (AI), in manufacturing companies' supply chain management (SCM) and production processes has been investigated over the past ten years [14, 15]. These technologies are thought to be a promising way to enhance supply chain operations like logistics, planning, scheduling, and procurement [15, 16].

The term "supply chain" refers to the movement of financial resources, materials, and information [16]. Adoption of ICT has made it possible for supply chains to keep an eye on information flow and has made them more likely to gather and examine a wide range of data for effective management. By 2020, there will be 35 Zeta bytes of digital data, which is predicted to rise exponentially [16, 17]. Companies nowadays are realizing more and more the importance of data and sophisticated analytics technologies. Over the past ten years, there has been a significant surge in the utilization of diverse Information and Communication Technologies (ICT) for Supply Chain Management (SCM). Examples of these technologies include RFID, Internet of Things (IoT), and Enterprise Resource Planning (ERP). Supply chains will evolve due to digitalization. The primary goal of the digital supply chain is to increase system awareness and intelligence so that it can adapt physical processes in the chain for best results [18]. Attaran (2020) present eight technologies which are mostly cited in the literature as shown in Fig. 1.

Inventory and supply chain digitalization can result in several advantages, such as improved asset utilization, higher uptime, lower inventory and warehousing costs, better supply chain decisions, increased transparency, fewer freight miles required for transportation, more flexible supply chain management, and more effective inbound supply chain. Improved supply chain management may also be implemented more easily with the use of sophisticated analytics and notification systems, which provide excellent accuracy and insightful data.

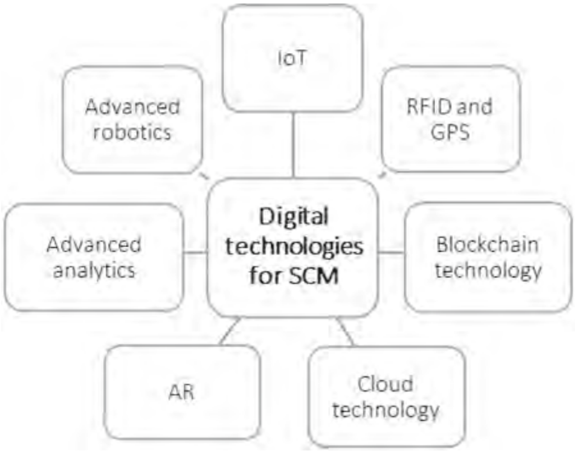

Fig. 1. Commonly integrated digital technology enablers for supply chains (Cited from Attaran, 2020) [18].

4 Digital Construction Inventory and Supply Chain Management Technologies

Upon closer examination, it is evident that a significant portion of waste generated in the construction industry stems from inadequate management of the material supply chain (e.g., delivery services, inventories, communications). Information technology (IT) is recommended in this context to improve logistics procedures and prevent delays. The literature has discussed several IT tools that can be utilized to enhance supply chain management and construction inventory integration. By IT, these apps have improved logistics performance by facilitating the mapping of time and cost resources, as well as transportation analysis and optimization models [19–21]. This section seeks to assess the most effective digital technologies utilized in supply chain management and inventory management systems for the construction industry for the reasons listed above.

4.1 Internet of Things (IoT)

The phrase "internet of things" (IoT) is a relatively new one in technology that refers to a state of connectedness between multiple objects at any one moment and place. The Internet of Things has already gained traction and is predicted to further digitalize inventory and supply chains. An Internet of Things (IoT) ecosystem makes information flow more smoothly, improving supply chain performance and giving operations advanced visibility. In an IoT-enabled environment, these technologies operate in four main phases: (1) data collecting, (2) data processing and transfer, (3) service, and (4) interface stages. They are supposed to show the data to the system's final user [22]. Radio frequency identification (RFID), wireless sensing, electronic labeling (EPC), global positioning systems (GPS), and reader devices are some of the technologies that permit Internet of Things applications. Because of the complexity of building projects and the high failure rate, which limits application, it is challenging for the construction industry to accept and embrace new technologies. IoT has been applied in the construction industry despite all of these challenges, and one of the most popular uses is the monitoring and control of project executions in a variety of projects, including onshore and offshore facilities, bridges, trains, tunnels, and other types of projects [23]. Additionally, according to Ding et al. (2013) it has been used to track building performance during emergencies, real-time safety alerts, and risk assessments [24]. IoT applications in building, such as smart city, smart home, and smart transportation design, were studied by Chandanshive and Arbaz (2017) [25].

4.2 Blockchain

The primary goal of blockchain is to provide network security, transparency, and visibility by integrating technologies including data encryption, storage systems, consensus algorithms, and smart contracts. A chain of linked blocks, each with a unique ID, is what is known as a blockchain. The system is transparent and safe because it makes it easy to trace transaction histories between blocks, particularly when those transactions are authenticated and approved by network users [22]. Numerous experts have determined that smart contracts are among the most useful blockchain-based solutions in the construction industry. After successful development, this system can be applied across the whole construction project lifespan, not only the planning stage. Well-known fusion applications of emerging technologies, such as blockchain, include smart cities and logistics, and several attempts in the building and operation and maintenance (O&M) phase are evident. IoT has been actively used in pilot projects to efficiently gather and handle construction data, and several types of blockchain technology are anticipated to be integrated into the development and upkeep of smart cities [26].

4.3 Cloud Computing

The manner both hardware and software resources are managed and used is changing dramatically with the advent of cloud computing. Sharing of the non-physical and physical components of an information technology (IT) infrastructure is made possible by the advent of Service Oriented Architecture (SOA), the foundation of cloud computing technologies. The concept is to distribute the expense of computing by making the infrastructure of computers reusable. The original investment expenses and operating costs of computing infrastructure are considerably decreased by these capabilities [27]. The use of cloud computing in the construction industry is a relatively new field with a lot of potential. Cloud computing also provides construction industries with reasonably priced, high-performance servers equipped with potent CPUs, GPUs, and lightning-fast SSD drives. It also offers a safe place to store the construction data on a secured platform. Furthermore, data kept on-site needs physical access, but data stored in the cloud can be remotely stored and retrieved at any time or location. Finally, the construction industry can be more productive and well-organized thanks to the cloud, which offers a central repository for construction data for an end-to-end solution.

4.4 Cyber-Physical Systems (CPs)

Cyber-physical systems (CPS) are systems that operate based on the combination of physical and computational processes. It is implemented with internet-connected computer-based algorithms under observation. It acts as a bridge connecting the real and virtual worlds. The shared knowledge and information between the computational decision components of CPS and the physical process enables adaptation, intelligence, and responsiveness [28]. The construction industry is a prime candidate for a step change, according to Kamara et al. (2000), because of its persistent issues with inadequate client satisfaction, inconsistent quality, delivery dates, and costs, relatively low productivity compared to other industries, and inefficiencies stemming from antiquated procedures [29]. For the industry to satisfy the constantly expanding needs in a variety of areas, a change in operations and procedures is critical. In the construction business now, CPS is not a well-known occurrence. Recent research has highlighted the potential for integrating CPS into the building process, nevertheless.

4.5 Digital Twins

Digital twins (DT) are a prevalent Industry 4.0 manufacturing technology that is commonly defined as a virtual clone of a physical asset with real-time two-way communication for simulation and decision-aiding features for improved product and service. DT is a cost-effective method for resource tracking, scenario simulation, and solution creation. It is frequently regarded as a flexible and scalable solution [30]. In the building and construction industry, digital twins (DT) first offer opportunities to simulate and improve the design and production-related activities, like the visualization of blueprints, the production schedules for prefab units, and the optimization of materials logistics. This is achieved by improving an automatic data acquisition and variation system. Second, by creating as-built models for building projects and associated facilities, DT realizes automatic and intelligent processes during the O&M stages in the construction industry. Buildings, facilities, and interior structures can be monitored and evaluated, among other basic O&M functions, using real-time physical condition updates [31].

4.6 Artificial Intelligence (AI) Systems and Machine Learning (ML)

Supply chain operations can greatly benefit from the application of Artificial Intelligence (AI). When compared to traditional methods, AI solutions have shown a great deal of promise for boosting automation and digitalization and creating competitive advantages [32]. AI is used to solve a variety of business problems and support decision-making for real-world issues. These subfields include machine learning (ML), computer vision, robotics, natural language processing (NLP), classification algorithms, fuzzy logic, optimization, and automated scheduling and planning. The integration of AI-based approaches in the best-term of each stage of the product life cycle is clarified by an intriguing study on the application of AI, ML, and Deep Learning (DL) in the product lifecycle. This includes the stages of conceptualization, design, building, operation, and maintenance [33]. There has been a fair amount of study over the past few decades on the use of artificial intelligence (AI) and its related domains to address issues in the construction industry. Based on the results of the research, an estimate of the benefits AI approaches can offer the CSC can be made. Machine Learning (ML) applications in site supervision, intelligent maintenance, automatic detection, health and safety monitoring, supply chain management, risk prediction, and logistics operations are a few of the more prominent ones [32].

5 Conclusion and Discussion

The utilization of digital technologies for inventory and supply chain management has been promoted as a means of enabling groundbreaking advancements in the construction industry, given the swift progress made in digitalization. As a result, a significant amount of research on supply chain management and digital inventory technology in the construction industry has been done over the past few decades, producing a large, dispersed, and varied body of knowledge. New and emerging technologies like blockchain, smart contracts, and the Internet of Things (IoT) are being investigated for possible use in construction inventory and supply chain management procedures through Industry 4.0, which focuses on digitalization and ubiquitous interactions. Nevertheless, a number of web-based technologies, including electronic procurement (e-procurement), e-commerce, and enterprise resource planning (ERP), were being adopted in this field, including material sourcing, supplier selection, tendering/bidding, and progress monitoring, prior to Industry 4.0 and its technologies. Therefore, this study aims to investigate web-based technologies in CSC management as a future research direction.

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