Joint CSCE Construction Specialty & CRC Conference 2025
Conférence conjointe spécialisée en construction de la SCGC et CRC-2025

Montreal, Quebec
July 28-31, 2025 / *28-31 juillet 2025*

The life cycle of timber construction enhanced with digital twin (DT), BIM, and robotics technologies

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ABSTRACT: By integrating the use of innovative technologies such as Digital Twin (DT), Building Information Modeling (BIM), and robotics, the lifecycle management of timber construction can be significantly enhanced, which leads to more effective, sustainable, and safer building systems. This paper aims to explore the applications and benefits of three innovative technologies (DT, BIM, and robotics) during the timber construction lifecycle. The data was collected from recent publications indexed in SCOPUS focusing on timber construction, DT, BIM, and robotics. DT presents data collection in real-time and dynamic simulations, supporting improved decision-making and collaboration between humans and robots during processes such as inspection and maintenance. BIM presents effective tools for lifecycle assessment, structural health monitoring, and design optimization, supporting resource-efficient and environmentally sustainable building techniques. Robotics increase the automation of on-site assembly, decreasing the cost of labor and increasing construction accuracy. BIM and DT technologies support robotic applications to improve construction automation, through accurate digital models and real-time feedback in the collaboration between humans and robots during the on-site assembly and processes of timber buildings. This review collects recent findings, identifies challenges and opportunities, provides insights into applying these technologies for sustainable timber construction, and outlines further research and practical applications.
Keyword; Timber Construction; Digital Twin; Building Information Modeling; Robotics in Construction; Sustainable Construction; Automation in Construction

1. INTRODUCTION AND BACKGROUND

Timber construction, while sustainable, faces numerous challenges, including limited long-term performance data, long-term durability, data integration inefficiencies, scalability issues, and on-site labor intensity. Emerging technologies such as Digital Twins (DT) offer dynamic simulations and real-time data insights, Building Information Modeling (BIM) enhances lifecycle visualization and coordination, and robotics enable automation and precision in tasks such as cutting and assembly address these by enabling predictive modeling, improved decision-making, automation, and seamless data exchange across lifecycle stages.

Engineered wood-based mass timber building technologies are becoming a sustainable alternative to multi-story concrete or steel-frame constructions. Due to their novelty, these structures' long-term performance is questionable. Thus, various structural health monitoring (SHM) projects have evolved to track their behavior. SHM project restrictions prevent the mass timber sector from using this data widely. These limits include scalability, data integration, different data-gathering tactics, lack of relevant data, data analysis complexity, and prediction tool usability (Riggio et al. 2022). Cross-laminated timber (CLT) is used in mass timber building, and mid-rise and high-rise projects are now available worldwide. According to scientometric review research comparing CLT with business 4.0 in the building business, Industry 4.0 deployment in cross-laminated wood is still in its infancy. No CLT research has been done on the digital twin idea, a popular building technology. Any research practice needs digital automation, and industrial robots can handle complicated geometries, making them crucial for CLT (Martinez Villanueva, Cardenas Castañeda, and Ahmad 2022). An existing modular Collective robotic construction system was improved, demonstrating its potential to manufacture full-scale in-plane timber structures. Using co-design methodologies, the robotic actuators were modified to account for material tolerance in the passive construction material, timber struts, which they utilize for movement and structural assembly (Leder et al. 2024).

A conceptual framework and computational workflow were developed to design and assemble a novel engineered wood structure for complex tectonic configurations, using robotic assembly, topology and material optimization, and combinatorial design logic. A DT was developed from robotic layered production for timber structures to voxel-based design of massive timber structures (Naboni and Kunic 2019; Chacón et al. 2024). DT technology enables real-time data collection and facilitates decision-making through dynamic simulation. It enhances collaboration between humans and robots in facility management tasks. This increases efficiency and effectiveness in executing tasks such as patrolling, inspection, and cleaning (Mazumder et al. 2023; Lu et al. 2023). Reconfigurable manufacturing systems solve the problems of increased product diversity and shorter product life cycles. This is particularly important when project components and needs change in timber building prefabrication. Reconfigurations must be fast to minimize downtime. Reconfiguration planning is complicated and requires DTs and industrial system simulation models for simulation and validation. In wood prefabrication, building components and specifications vary with each project; hence, the production system must be reconfigured often. Building components and manufacturing system configuration are co-designed to maintain manufacturing process integrity in a changing production environment. Thus, several planning iterations may be needed. Each iteration requires simulation validation. However, manual simulation model production is time-consuming and error-prone, limiting digital planning (Kaiser, Reichle, and Verl 2022). The Forest2Building DT Framework (F2BDF) was developed to provide an in-depth view of the entire wood construction supply chain and its complete life cycle, which includes all phases from forest biological production and raw material supply to product processing and engineering, installation, and utilization in buildings, and recovery during deconstruction (Ott et al. 2023).

An adaptive slab system that includes thin Cross-Laminated Timber panels and robot-fabricated beam networks for reinforcement was outlined; the beam network was established through a complex interplay of structural optimization and fabrication limitations, allowing for adaptability to variations in slab span and orientation (Chai et al. 2022). A framework was developed to close the gap between the design and robotic assembly of timber structures, highlighting an effective automation process that utilizes learning by demonstration to master the intricate assembly of an interlocking wooden joint. This overview encompasses various focal points, ranging from integrating a digital twin to timber joint design and robotic assembly execution, as well as the creation of a flexible robotic configuration and innovative assembly techniques to address the complexities of the designed timber joints (Kramberger et al. 2022). A design was developed for the automated on-site assembly of high-payload, full-scale, form-fit timber parts, demonstrating the automated process at an actual building site. All methodologies are outlined, including the creation of two comprehensive on-site assembly manipulators and end-effectors for the tasks of picking, transporting, placing, and connecting components, as well as automated data extraction from the BIM model, path planning, trajectory generation, feedback control, and empirical evaluations using robotic total station measurements (Lauer et al. 2023).

A comprehensive study was presented to exploit the applications, innovative approaches, and capabilities of BIM, Virtual Reality (VR), and gamification. A game-like platform combined with BIM improves design quality and minimizes possible rework in manufacturing, assembly, and construction sectors through automation. Also, enhancing the current collaboration workflow in BIM standards by establishing a direct connection with the customer during the design phase (Potseluyko et al. 2022). BIM offers significant benefits in information integration, visualization, and secondary development, and its implementation in structural health monitoring can address these issues. A BIM-based management platform was developed with the nD BIM model that integrated multi-source information for enhanced and efficient preservation of heritage timber structures (Wang et al. 2022). A quantitative Life Cycle Assessment (LCA) approach was used to evaluate, during the design phase, the impact on the environment generated by a timber-frame single-family residence compared to those of a concrete-masonry house constructed in Uruguay. The technique, designed as a decision-making instrument, combines BIM and LCA to assess and contrast the environmental implications of a prevalent housing typology in Uruguay (Soust-Verdaguer, Llatas, and Moya 2020).

Despite a growing body of research on Digital Twin, BIM, and robotics applications in timber construction, several gaps persist. Most notably, there is a lack of studies that explore the integrated use of these technologies across the entire lifecycle of timber buildings. Existing research often focuses on individual applications (e.g., DT for monitoring or BIM for design coordination), with limited evaluation of their interoperability or combined impact. Few studies provide detailed methodologies for implementation or assessing long-term sustainability outcomes, especially in real-world projects. These gaps highlight the need for a comprehensive review and a unified framework that bridges these digital tools to support lifecycle management in timber construction.

This study focuses on exploring aspects of new technologies such as DTs, BIM, and robotics in timber construction by addressing specific research questions regarding these technologies for the construction industry:

Q1: What are the applications of the new technologies such as DTs, BIM, and robotics in timber construction?

Q2: What are the benefits of new technologies such as DTs, BIM, and robotics in the life cycle of timber construction?

Thus, this study thoroughly reviews the applications and benefits of DTs, BIM, and robotics in timber construction. To grasp the current applications of these technologies in timber construction, this study evaluates existing research evidence, applying the PRISMA criteria up to January 2025.

2. RESEARCH METHODOLOGY

A systematic literature review was conducted using the PRISMA method. Peer-reviewed SCOPUS-indexed articles were selected up to January 2025. Inclusion criteria were relevant to DT, BIM, and robotics applications in timber construction. Studies were filtered based on relevance, publication quality, and technological focus. Excluded studies included non-English papers and those lacking direct application to timber lifecycle stages. By integrating DTs, BIM, and robotics technologies, the lifecycle of timber construction can be significantly enhanced, which leads to more effective, sustainable, and safe building systems. To achieve the research aims and fulfill the literature gap, the research method is organized as shown in Figure 1.

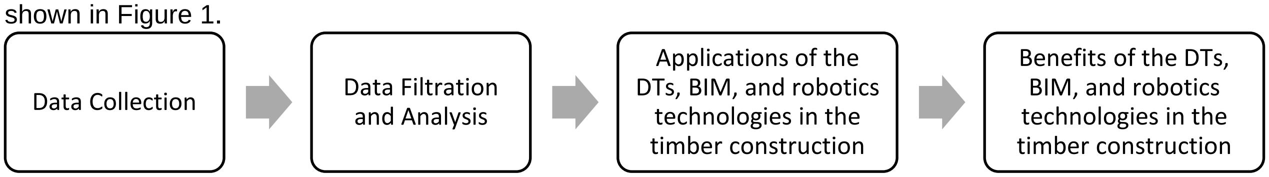


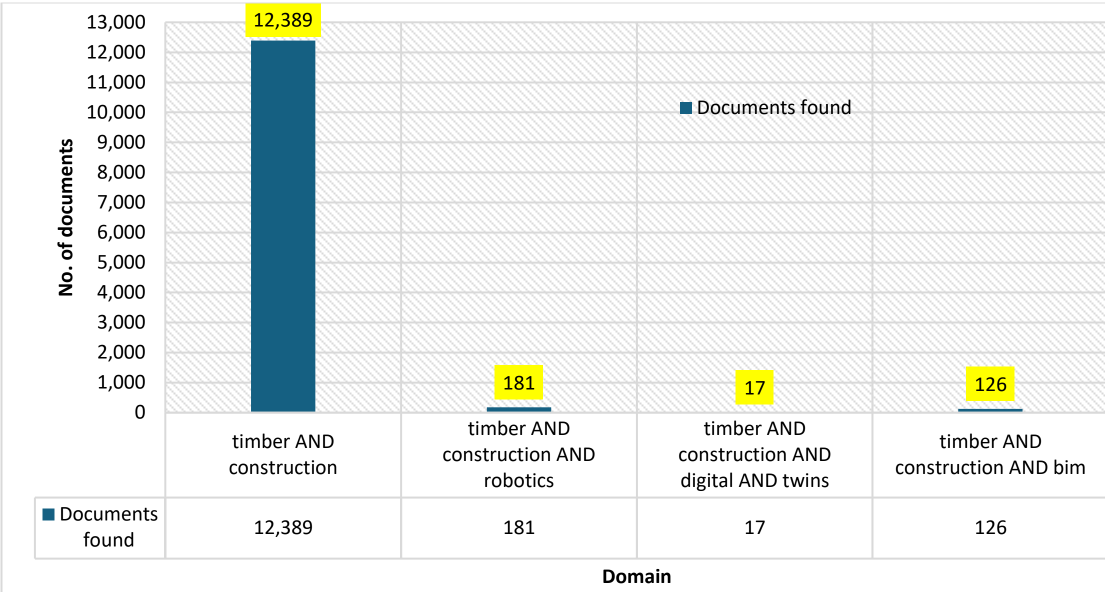
Figure 1: Research Methodology

2.1 DATA COLLECTION

For related research papers, the authors reviewed Scopus databases in the below domain, as shown in Figure 2:

- timber AND construction (12,389 documents found)
- timber AND construction AND robotics (181 documents found)
- timber AND construction AND digital AND twins (17 documents found)
- timber AND construction AND BIM (126 documents found)

This literature survey is based on articles on timber construction, BIM, robotics, and digital twins obtained in reputable academic journals up to January 2025.



	timber AND construction	timber AND construction AND robotics	timber AND construction AND digital AND twins	timber AND construction AND bim
Documents found	12,389	181	17	126

Figure 2: Domain and documents found

2.2 DATA ANALYSIS

The data analysis section in this study focuses on recent publications and case studies collected from SCOPUS-indexed publications. It focuses on DT, BIM, and robotics in timber construction with a thorough classification of findings across various subject areas, as shown in Figure 3 and Table 1.

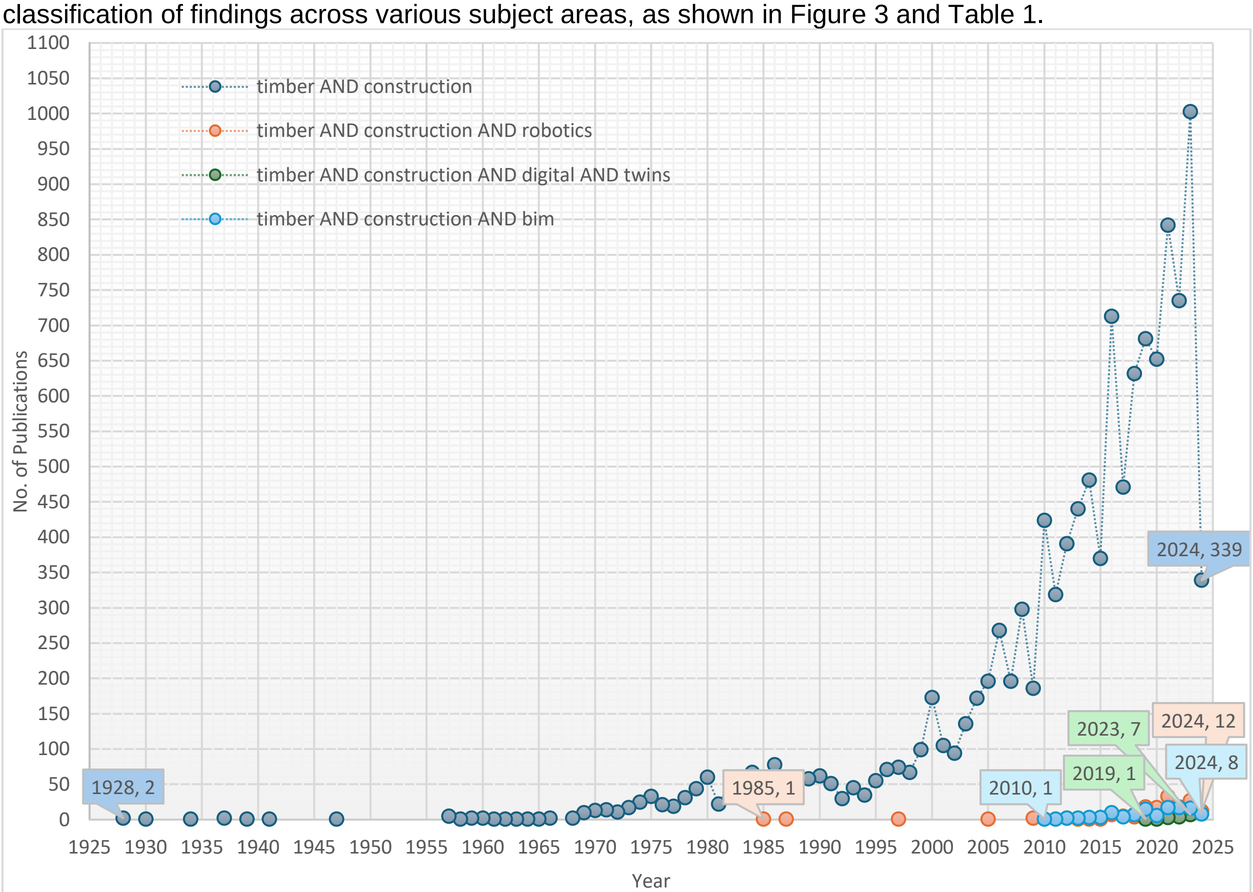
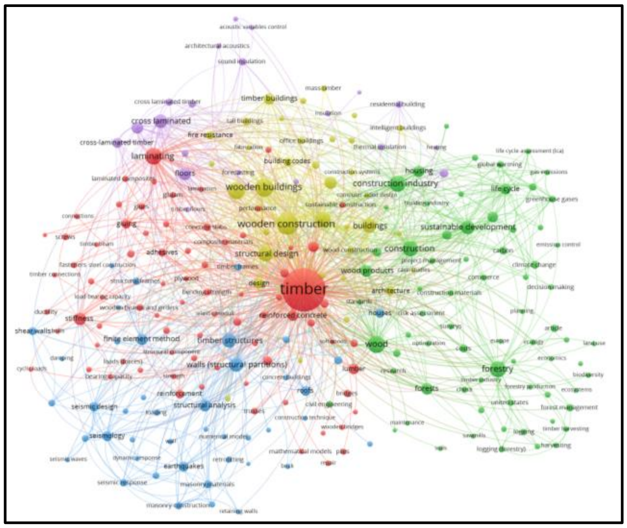


Figure 3: Classification according to "Year"

Table 1: Classification according to "subject area"

Subject Area	timber AND construction	timber AND construction AND robotics	timber AND construction AND digital AND twins	timber AND construction AND BIM
Engineering	6,662	117	14	83
Agricultural and Biological Sciences	3,026	20	4	18
Materials Science	1,828	9		3
Environmental Science	1,634	5		13
Social Sciences	1,131	17	2	13
Arts and Humanities	906	9		9
Earth and Planetary Sciences	806	8		7
Computer Science	610	63	7	23
Physics and Astronomy	555	5		4
Energy	501	2		8
Chemical Engineering	415	4		3
Business, Management and Accounting	247	2	1	6
Mathematics	191	7	1	6
Chemistry	171			
Economics, Econometrics and Finance	118			
Medicine	106	1		
Multidisciplinary	92			1
Biochemistry, Genetics and Molecular Biology	85	1		
Decision Sciences	63	2		2
Immunology and Microbiology	24			
Pharmacology, Toxicology and Pharmaceutics	9			
Health Professions	7			
Psychology	6			
Veterinary	5			
Neuroscience	5			
Nursing	1			

The visualization map represents key thematic networks in timber construction, integrating DTs, BIM, and robotics. Figure 4 illustrates the broad research in timber construction; this network visualization highlights the relationships and research themes. The central node, "timber", is surrounded by terms like "wooden construction," "sustainability," and "material efficiency," which are key focus areas. Figure 5 highlights robotics' impact, showcasing how automation and precision manufacturing enhance efficiency and reduce labor-intensive tasks in timber projects. The central node, "robotics", is linked to terms such as "automation," "fabrication," and "robotic assembly," indicating robotics' impact on construction processes. Figure 6 emphasizes the role of BIM in streamlining design, lifecycle assessment, and promoting sustainable practices. The central term "BIM" is connected to topics like "architectural design," "sustainability analysis," and "prefabrication," highlighting the role of BIM in timber construction. Figure 7 explores emerging applications of DTs for real-time monitoring, predictive maintenance, and improved lifecycle management, though it remains an area with significant research potential. The central node, "digital twin," connects to terms like "real-time monitoring," "simulation," and "predictive maintenance," which indicate DT's advanced applications.



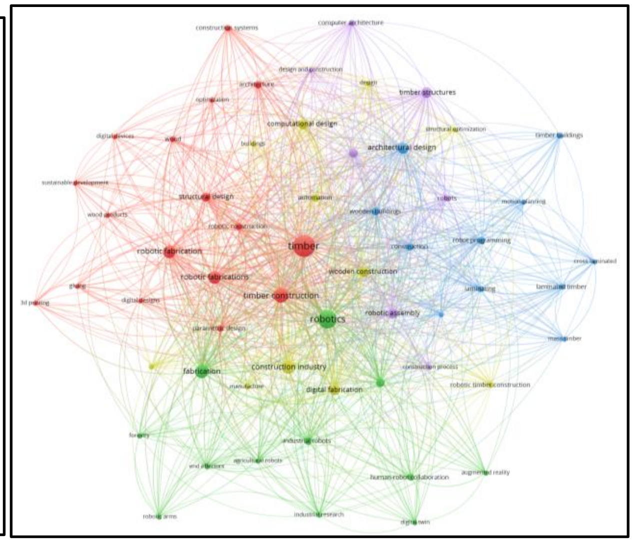
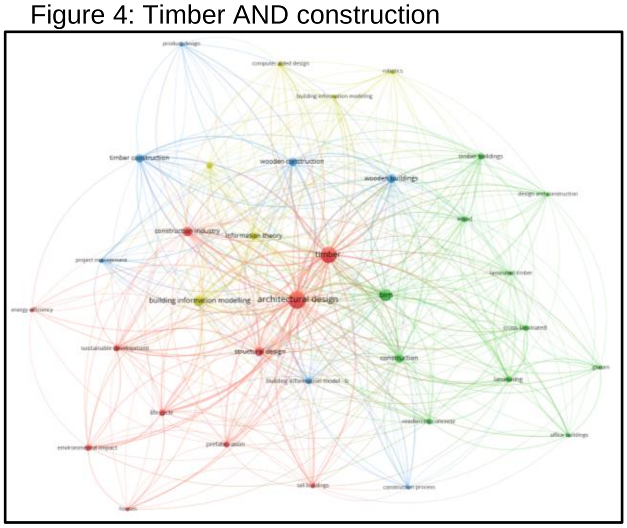


Figure 4: Timber AND construction

Figure 5: Timber AND construction AND robotics



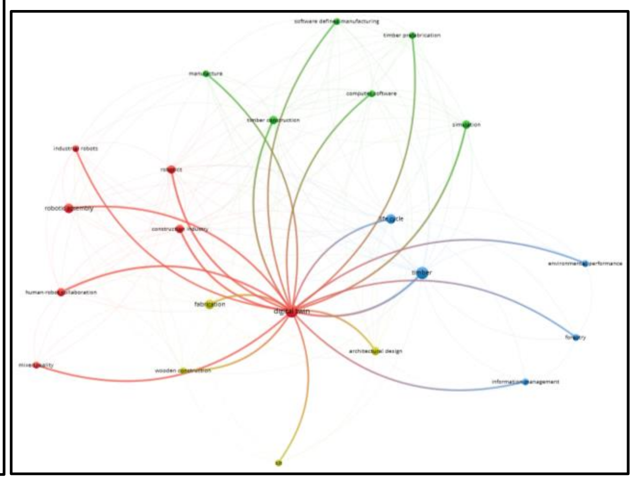


Figure 6: Timber AND construction AND BIM

Figure 7: Timber AND construction AND digital AND twins

3. APPLICATIONS OF THE DTS, BIM, AND ROBOTICS IN TIMBER CONSTRUCTION

In contrast to earlier studies that often isolate DT, BIM, or robotics as stand-alone innovations, this paper emphasizes their synergistic potential when integrated across timber construction phases. For instance, while Chacón et al. (2024) demonstrate DT's utility in dynamic monitoring, Lauer et al. (2023) apply robotics for on-site timber assembly. Yet, few studies have critically evaluated their combined deployment. Our analysis bridges this gap, comparing case studies to highlight overlapping efficiencies, such as real-time BIM-data feedback improving robotic assembly precision or DT-informed planning reducing site adaptation time. This synthesis underscores the necessity of cross-technology frameworks rather than siloed applications.

Several real-world case studies underscore the practical integration of these technologies. The Forest2Building DT Framework maps timber supply chains across full lifecycles. Robotic timber joint assembly systems demonstrate adaptability to material variances, and adaptive CLT slab systems showcase how robotics enhance flexibility and construction precision.

This section presents the main applications of DTs, BIM, and robotics in timber construction, as shown in Figure 8. DTs are used to create virtual models of timber structures, allowing real-time monitoring, dynamic simulations, and predictive analysis. Applications include optimizing prefabrication processes, facility management, and collaborative activities between humans and robots, including inspection and maintenance. BIM performs as a collaborative platform for 3D modeling, lifecycle assessment, and structural health monitoring. BIM also improves coordination and decision-making during the design and construction phases, reducing errors and improving project outcomes. Robotics in timber construction automates repetitive and labor-intensive tasks, including cutting, assembly, and on-site installation. Applications include robotic arms for timber joint assembly, drones for site monitoring, and automated data extraction from BIM models for job optimization.

Automated systems for the prefabrication and on-site assembly of timber structures improve productivity and reduce labor shortages (Lauer et al., 2023).
BIM integrates with Life Cycle Assessment (LCA) for environmental impact assessments during the design stages, aiding in the decision-making process for sustainable timber construction projects (Soust-Verdaguer et al., 2020).
Robots can be used for the on-site assembly of timber components handling tasks such as picking, placing, and fastening elements with high precision (Riggio et al., 2022).
DT and BIM are used for ongoing structural health monitoring, predicting potential issues, and enabling proactive maintenance of timber structures (Riggio et al., 2022).
BIM and DT technologies facilitate advanced design and simulation processes, enabling the creation of complex timber structures optimized for performance and durability (Riggio et al., 2022).
Timber components can be prefabricated using robotic systems, ensuring high precision and quality while reducing construction time and labor costs (Riggio et al., 2022).
Robotics and DTs are used to automate the on-site assembly of timber structures, including complex joints and large-scale elements, ensuring precise placement and alignment (Lauer et al., 2023).
BIM integration allows for data extraction for path planning and trajectory generation, enabling automated assembly processes (Kramberger et al., 2022)(Lauer et al., 2023).
DTs provide real-time monitoring and predictive maintenance of timber buildings, ensuring long-term structural integrity and performance (Chai et al., 2022)(Mazumder et al., 2023).
Robotic systems facilitate high-precision prefabrication of timber components, allowing for customized designs and complex architectural forms that would be challenging to achieve manually (Kramberger et al., 2022)(Naboni et al., 2019).
Digital twins and BIM can facilitate mass customization in timber construction, allowing for tailored designs that meet specific client needs while maintaining cost efficiency (Chacón et al., 2024).
Robotics and BIM can be integrated to enhance the manufacturing and assembly of prefabricated timber components, improving efficiency and accuracy in construction (Chacón et al., 2024).
BIM and digital twins can be used to monitor and manage the structural health of heritage timber structures, ensuring their preservation and safety over time (Wang et al., 2022).

Figure 8: Summary of the applications of DTs, BIM, and robotics in timber construction

4. BENEFITS OF DTS, BIM, AND ROBOTICS IN TIMBER CONSTRUCTION

Integrating DTs, BIM, and robotics in timber construction provides major efficiency, sustainability, cost-effectiveness, and safety benefits, as shown in Figure 9.

Sustainability and Environmental

- Timber construction, supported by robotics and BIM, reduces the carbon footprint by minimizing waste and utilizing renewable resources like wood, which can be grown (Lauer et al., 2023).
- Robotics and automation in timber construction can reduce waste, improve material efficiency, and lower the carbon footprint, contributing to more sustainable building practices (Riggio et al., 2022).
- BIM-based LCA methods allow for the comparison and optimization of timber construction projects, showing that timber buildings can produce lower environmental impacts in terms of Global Warming Potential and other metrics compared to traditional concrete structures (Leder et al., 2024) (Soust-Verdaguer et al., 2020).
- Integrating these technologies can lead to more sustainable construction practices by optimizing material use and reducing waste. This is particularly relevant in the timber construction industry, where sustainability is a key concern (Chacón et al., 2024).

Enhanced Decision-Making and Visualization

- BIM facilitates information integration, visualization, and secondary development, which are crucial for the effective management of heritage timber structures (Wang et al., 2022).
- Integrating BIM with robotics allows for precise fabrication and assembly of timber structures, reducing errors and improving the overall quality of construction (Riggio et al., 2022).

Real-Time Monitoring and Maintenance

- BIM-based structural health monitoring systems can integrate various data sources to provide early warnings and help in the proactive maintenance of timber structures (Wang et al., 2022).
- Digital twins enable continuous monitoring and analysis of construction parameters, which can lead to timely maintenance and adjustments to enhance the longevity of timber structures (Wang et al., 2022)(Chacón et al., 2024).
- DT enhances the management of the entire lifecycle of timber buildings by providing real-time data and predictive analytics to optimize maintenance and operational efficiency (Riggio et al., 2022).

Improved Productivity and Resource Efficiency

- BIM-driven computational design enhances the precision and quality of timber structures by integrating detailed modeling with automated manufacturing processes (Chai et al., 2022)(Chacón et al., 2024).
- By utilizing robotics and automated systems, the risk of accidents on construction sites can be significantly reduced, leading to safer working environments (Riggio et al., 2022).
- Using robotics in timber construction allows for high-precision prefabrication and on-site assembly of timber components, facilitating the creation of complex and customized building designs (Chai et al., 2022)(Lauer et al., 2023).

Figure 9: Summary of Benefits of DTs, BIM, and robotics in timber construction

While integrating DT, BIM, and robotics offers transformative potential for timber construction, several implementation challenges persist. These include technical interoperability between platforms, high initial investment costs, limited digital skills among the construction workforce, and the lack of standardized protocols for integrating DT and robotics with BIM environments. Data security and ownership concerns, fragmented project delivery models, and resistance to change within traditional construction practices can impede adoption. The complexity of coordinating across diverse stakeholders further exacerbates these issues, especially in small- and medium-sized enterprises (SMEs) where resources are constrained. Addressing these limitations requires tailored frameworks, training programs, and policy incentives to foster scalable adoption.

5. CONCLUSIONS AND FUTURE WORK

A strategic roadmap is essential for advancing research. Key areas include integrating AI-driven analytics with DT, developing interoperable BIM-robotics systems, and piloting long-term monitoring for sustainability validation. Future research should address how small- to mid-size companies can scale these technologies and identify policies that support digital innovation in the timber construction sector.

Integrating DTs, BIM, and robotics is transforming the timber construction industry. These technologies collectively improve efficiency, sustainability, and safety by solving critical challenges in lifecycle management, as shown in Table 2. This study highlights the importance of these innovations in achieving a sustainable and automated future for timber construction. These innovations can enable sustainable innovation and development in timber construction through increasing collaboration among academia, industry, and policymakers. Future research should focus on:

- Creating advanced models and algorithms to optimize the integration of DTs, BIM, and robotics.
- Exploring the impact and role of AI in improving timber construction processes.
- Implementing longitudinal studies to assess long-term impacts on performance and sustainability.

Table 2: Mapping of DT, BIM, and Robotics Applications Across Timber Construction Lifecycle Phases

Lifecycle Stage	DT	BIM	Robotics
Design	Simulation and design optimization	3D modeling, clash detection, lifecycle assessment	Assisted design for robotic feasibility
Prefabrication	Production planning and real-time digital feedback	Material estimation, prefabrication planning	Automated cutting and component preparation
Construction	Site monitoring and digital coordination	Construction sequencing, document control	Robotic on-site assembly and inspection
Operation& Maintenance	Real-time monitoring, predictive maintenance	Structural health monitoring, data management	Robotic inspection and cleaning
End-of-Life	Deconstruction planning, resource tracking	Lifecycle analysis, demolition documentation	Disassembly and recycling

6. ACKNOWLEDGEMENTS

The authors would like to thank the National Science Foundation (NSF). This material is based on work supported by the NSF under Grant No. 1827733. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF.

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