

Review of Advances in the Robotization of Timber Construction

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Abstract

The construction industry faces persistent productivity shortfalls and rising carbon dioxide emissions, which drives a shift toward the use of low-carbon materials and higher degrees of automation. Timber, a renewable and carbon-sequestering material, becomes especially compelling when combined with robotic fabrication. Although rapid advances have been implemented in the last decade, research and practice remain fragmented, and systematic evaluations of technological readiness are scarce. This gap is addressed in this review through critical literature synthesis of robotic timber construction, combining bibliometric analysis with a comparative evaluation of twelve representative case studies from 2020 to 2025. Computational and robotic tools are mapped across the design to fabrication pipeline, and emerging advancements are identified such as digital twins, real-time adaptive workflows, and machine learning driven fabrication, alongside discrete and circular strategies. Barriers to scale up are also assessed, including mid-level technology readiness, regulatory and safety obligations for human–robot interaction, evidence on cost and productivity, and workforce training needs. By clarifying the current level of robotization and specifying both research gaps and industrial prerequisites, this study provides a structured foundation for the next phase of development. It helps scholars by consolidating methods and metrics for rigorous evaluation, and it helps practitioners by highlighting pathways to scalable, certifiable, and circular deployment that align cost, safety, and training requirements.



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1. Introduction

The building construction industry is responsible for high carbon emissions, significant resource waste, and persistently low production efficiency [1,2]. With the rise in carbon dioxide emissions acknowledged as the primary driver of climate change, a shift in the construction industry towards more sustainable practices and the use of renewable materials is increasingly implemented [3]. Wood, being a widely utilized building material, is not only renewable it also serves as a natural carbon sink, which implies that it absorbs and stores more carbon dioxide from the atmosphere than it releases [4]. The Global Status Report [5] for Buildings and Construction identifies that, in 2022, buildings accounted for 37% of energy and process-related CO₂ emissions with sector emissions rising compared to 2021, thus underscoring the urgency of advancing low-carbon construction approaches.

National and regional policies now increasingly position timber within a circular economy agenda with UK Timber in Construction Roadmap for instance setting out near-term actions to increase timber uptake through modern methods of construction [6].

In parallel with these policy-driven initiatives, advancements in digital and automation technologies have also begun reshaping construction practices. More recently, artificial intelligence (AI) and robotics have infiltrated architecture and building construction in various capacities, from automating routine tasks to executing large-scale operations through human–machine collaboration, thereby creating new workflows [7,8]. Various applications show considerable levels of automation significantly improving the efficiency, quality, and sustainability of construction projects [9–11].

By integrating advanced automation into design, fabrication, and assembly processes, robotic timber construction addresses critical challenges in material efficiency, labor productivity, and sustainability [12]. Overall robotics has the potential to positively influence 46% of the Sustainable Development Goals (SDG), particularly those related to industry and the environment, significantly transforming production systems and societal frameworks [13,14].

In recent years, discrete automation using robotics, AI, and industrial automation systems optimize manufacturing processes that involve discrete elements [15]. Such scalable approach to computational design and manufacturing facilitates mass production of self-similar elements. The main consideration is that robotized vs. conventional computer-numerically controlled (CNC) approaches are (a) more capable of handling complex geometries [16] due to multiple degrees of freedom, allowing robots to reach and manipulate objects in a three-dimensional space more easily and (b) more flexible in terms of the range of tasks and materials they can handle compared to CNC machines, which are usually specialized for specific tasks. Hence, multi-robot systems can simultaneously or in short sequence implement various tasks.

In this context, robotic timber construction emerges at the intersection of low-carbon materials and precision automation. For instance, a Learning-by-Demonstration (LbD) assembly of interlocking timber trusses achieved 0.5 mm fabrication tolerance on milled studs and 93% successful executions ($n = 100$) across varied poses [17] demonstrating along with other AI-enabled applications [18] and circular timber workflows their potential to improve accuracy [19], reduce waste [20], and support design-for-disassembly and reuse [21].

Related Work and Contribution

This paper discusses advancements of automated technologies in the timber construction industry, focusing on the design to construction methods and addressing their scalability for industrial level. Previous overviews of timber automation have typically emphasized individual platforms, case narratives, or fabrication typologies. In contrast, this review provides a data-informed synthesis that (a) maps 2020–25 themes with Visualization of Similarities (VOS) viewer; (b) normalizes twelve representative cases at Technology Readiness Level (TRL), Human–Robot Interaction (HRI), AI integration, and circularity levels; (c) derives cross-case patterns and gaps (e.g., factory vs. on-site AI roles); and (d) frames deployment pathways for interfaces, training, and circular reporting.

To achieve this, the manuscript employs two complementary layers of analysis: Section 2 synthesizes the state-of-the-art based on well-documented research exemplars, prototypes, and industrial applications that are widely cited, methodologically detailed, and influential in shaping the field. Section 3 complements this with a systematic bibliometric mapping of recent publications (2020–25, Scopus), capturing broader research dynamics, emerging trends, and consolidating twelve cases into a comparative table. Together, the

top-down review and the bottom-up bibliometric evidence provide a consistent and integrated assessment of the field, which then informs the synthesis and discussion presented in Section 4.

2. State-of-the-Art

Fueled by the insight that circularity in wood construction has inherent advantages such as lower lifecycle emissions and energy consumption compared to non-wood materials [22] and concurrent with advances in computational design and manufacturing, the growing interest in circular approaches and robotic timber construction has been focus of various experiments and studies. One prominent example of innovation in this field comes from the Eidgenössische Technische Hochschule (ETH) Zürich, which began already in 2008 to develop robotic assembly processes based on a material-efficient construction typology developed by Zollinger at the beginning of the 20th century [23]. Later, they experimented with other typologies implemented with one or more robots (Figure 1) aiming at advancing semi-/automation in construction.



Figure 1. Robotically assembled prototypes using one or more robots: precise robotic placement of short, interlocking timber elements into a diamond grid (**left**) and gantry-based system (**right**). © ETH Zurich [23].

Against this backdrop, robotic timber construction is rapidly maturing and nearing technology readiness level for large-scale implementation [24]. However, despite these advancements, many structures are still largely built using conventional CNC machining of components followed by manual assembly, which leads to labor-intensive fabrication routines and significant waste of resources.

2.1. Construction Automation

Expecting that about 50% of all tasks can be automated, while 45% are human–robot interaction (HRI)-supported, and 5% remain in human hands [25], identifying what tasks can be fully automated vs. HRI-supported requires examining the various tasks that robots can perform. Automating existing processes typically involves a top-down workflow. First, the desired design of the structure or building is defined based on the specific site, functional, structural requirements, etc. Following this, specific robotic instructions are developed (e.g., pick up element, move it to a specified location, position it, fix it in place, and release it). These instructions are generally predefined for each element to avoid real-time calculation during construction and to maintain maximum control over the processes. Finally, these instructions are executed by the robot [26]. More recently, feedback loops replace such linear approaches, with the fabrication procedures and the materialization constraints being considered from the very beginning of the process.

While the design is increasingly informed by production and assembly requirements, both on- and off-site processes are being advanced with some degree of HRI support. For instance, HRI-supported assembly has been developed at Technical University (TU) Delft using computer vision (CV) for object detection and control algorithms (Figure 2) allowing humans and robots to work together on the implementation of tasks [27]. For visual-served insertion of plate joints, fiducial-marker guidance was validated on >50 LVL samples (39 mm) and a two-tenon insertion demo [28]. Typical fabrication tolerances of ~1 mm were handled by self-centering geometries, while prior field precedents reported ~4 cm conic tolerance in large-module assembly to absorb crane swing.



Figure 2. CV and HRI assembly of scaled prototype. Robots equipped with CV recognize and manipulate irregular timber blocks (**left**) and (**center**), while the (**right**) image shows collaborative task-sharing with a researcher. © TU Delft [27].

TU Delft's HRI-supported approach involves two main aspects, the design of the parts, i.e., building components, and the design of the assembly based on robotic production and assembly constraints. The robotic assembly relies on automated and HRI-supported processes that require robots to be able to learn and re-plan the collaborative actions during the collaboration. The AI system of the robot incorporates CV and real-time planning techniques to account for both low-level skills (physical interaction and movement primitives) and high-level skills (when and how to perform certain actions or movements).

When combined with circular approaches, additional decrease in environmental impact is expected: for instance, using CV to identify, select, and robotically process reclaimed wood into timber components that are assembled into larger structures contributes to the advancement of sustainable practices [29].

While automation in timber construction has demonstrated sub-millimeter precision and robust repeatability, approaches diverge significantly in handling contact-rich tasks and unexpected deviations. Learning-by-demonstration and scripted pipelines are quick to implement but brittle under material variance, whereas force/torque-guarded controllers improve robustness but depend heavily on sensor bandwidth and joint geometry. Fixture-based methods perform well for throughput, while perception-driven workflows sacrifice speed to absorb larger tolerances. The research frontier is therefore not only technical capacity but also benchmarking: reported metrics such as pose error (mm), success rates, and recovery times remain sparse. A common evaluation framework is needed to compare throughput, accuracy, and robustness across automation platforms.

2.2. Prefabrication

Automated prefabrication of timber elements has been demonstrated in various research studies and projects in recent decades [30,31], with the advantages of prefabrication over on-site construction being identified as increased precision and accuracy as well as improved process efficiency and resource utilization [32]. Prefabrication systems draw upon concepts of reconfigurable factories, agile production networks, and decentralized manufacturing (Figure 3), designed to rapidly adapt to evolving market demands. Recent evidence quantifies the gains typically attributed to automated/off-site production. A

comparative review reports ~40% shorter construction time and ~30% lower costs for prefabrication relative to conventional delivery, with construction waste cut from 10 to 15% to <5% through factory controls and standardization [33]. A recent life-cycle accounting framework for prefabricated buildings estimates the materialization phase carbon footprint at ~378 kg CO₂/m², with the building material production component alone accounting for around 88% of that total [34]. Thus, prefabrication has the potential to reduce greenhouse gas emissions, energy use, and construction waste, especially when upstream (material, manufacturing) emissions are managed carefully.

When comparing off-site robotic prefabrication to conventional prefabrication the former can reduce embodied greenhouse gases (GHG) emissions by ~20–30% and waste rates from 10 to 15% down to ~5%, depending on structural systems and logistics [35]. Furthermore, studies have shown that prefabrication can reduce GHG emissions, energy use, and construction waste, contributing to a lower environmental footprint. The resulting decrease in the environmental footprint further underscores the transformative potential of automated prefabrication in timber construction [36].



Figure 3. Pre-assembly timber component (left) and on-site assembly of large components (right) © U Stuttgart [37].

While automation has improved throughput and precision, it has yet to fully leverage the unique affordances of robotics, such as multi-material assembly and non-planar joining strategies. Moreover, many robotic prefabrication methods focus on increasing formal complexity, with fewer addressing material efficiency, multi-material transitions, or platform-agnostic adaptability. Future reporting will normalize these values to enable more rigorous assessment of prefabricated timber systems.

2.3. On-Site Construction

Automated on-site construction involves, to some degree, HRI [38], to facilitate safe implementation of construction tasks. Due to the unstructured environment of architectural sites, on-site robotic construction requires feedback from the physical environment relying on sensors to supply the robot with real-time data [39]. Despite on-site construction challenges various studies are devoted to advancing research in this area. For instance, mobile multi-robot swarms (Figure 4) are explored for completing the automated on-site assembly of timber structures relying on sensors, and feedback processes [11,40].

The integration of AI into teleoperated, virtual reality (VR)-controlled on-site robotic applications represents a promising avenue for advancing timber automation in construction. These technologies offer the potential to enhance precision, adaptability, and efficiency in complex construction environments. VR interfaces have been employed to enable robotic control for tasks such as timber frame assembly [41] and intuitive design to fabrication processes [42]. These applications simulate site operations, allowing for detailed previsual-

ization, real-time adjustments, and improved coordination between human operators and robotic systems.

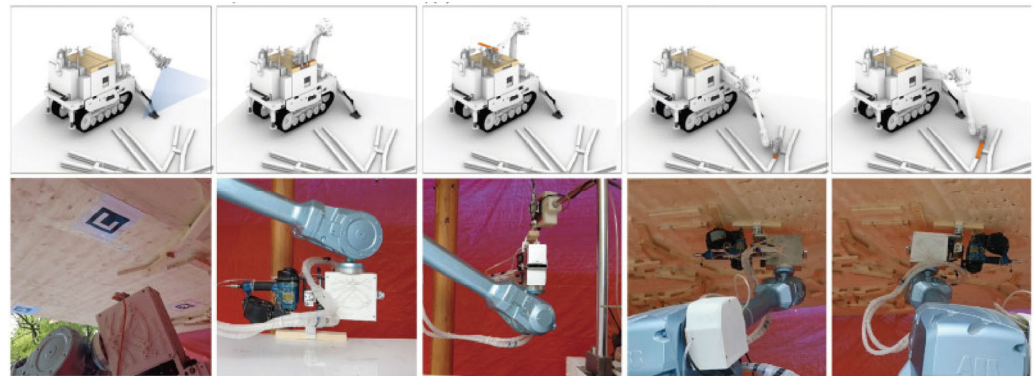


Figure 4. On-site fabrication scenario repeating workflow of five routines, scan, pick, glue, place, nail beam process © U Tongji [11,40].

Currently, on-site robotic construction mainly focuses on additive manufacturing (AM), automated installation systems, and robotic assembly systems [43]. These approaches typically address individual construction activities rather than integrated construction tasks. The question for robotic timber construction remains how to integrate all tasks and in which way this integration will impact discrete architecture.

The combination of on- and off-site construction leverages the advantages of both by providing flexibility for adaptations required during the on-site construction process and higher precision and faster off-site production since environmental variables like weather delays are minimized.

In this context, AI offers numerous opportunities to enhance efficiency, precision, and sustainability of design to timber construction processes [44]. For instance, École Polytechnique Fédérale de Lausanne (EPFL) developed integrated design tools for timber plate structures (Figure 5) [45]. Compatible timber joints are automatically created by interpreting an assembly sequence set by the designer and the 3D model generation of Integrally Attached Timber Plate (IATP) structures [46,47].

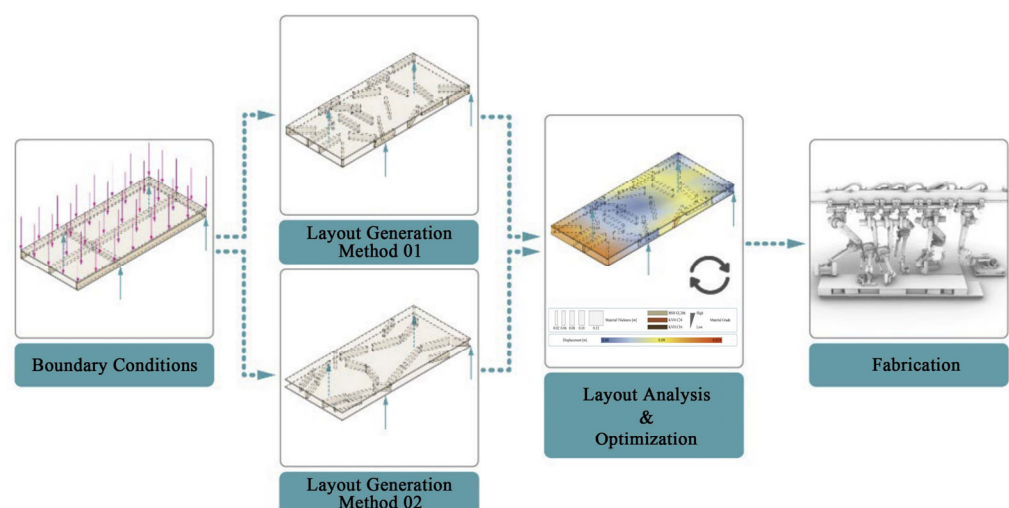


Figure 5. Continuous workflow of computational design, optimization, and robotic fabrication steps for constructing planar timber slabs © EPFL.

Furthermore, for achieving material efficiency, AI algorithms and digital machining tools are utilized to scan raw logs, convert them into boards, and optimize their arrangement

for cutting and assembling [48]. Demonstrating superior performance in path optimization, they reduced material waste by 17% compared to conventional CNC machining manufacture in mortise and tenon structures [49]. Complementary on-site systems (e.g., mobile robotic assembly of adaptive cross-laminated timber (CLT) reinforcement networks and biomimetic shell assembly) document workflows and hardware but do not yet report standardized figures such as per-element install time, error rates, or rework percentages; these remain promising targets for future benchmark reporting [50].

The continuous workflow, ranging from computational design to optimization, and robotic fabrication require developing an understanding of the discrete architecture approach (Figure 5).

2.4. Discrete Architecture

In discrete architecture, the emphasis is on discrete elements or modules, i.e., components that are assembled into larger structures. The rule-based composition of a finite set of part types (units or joints) with an explicit assembly grammar and reversible joining enables reconfiguration and reuse [51]; it starts with the individual elements and their relationship to other elements and progressively extending to form the overall design. For instance, a discretized growth approach employing a free-form cellular growth algorithm (Figure 6) utilizes the emerging qualities of growth simulations for a developing feasible architectural design [52].

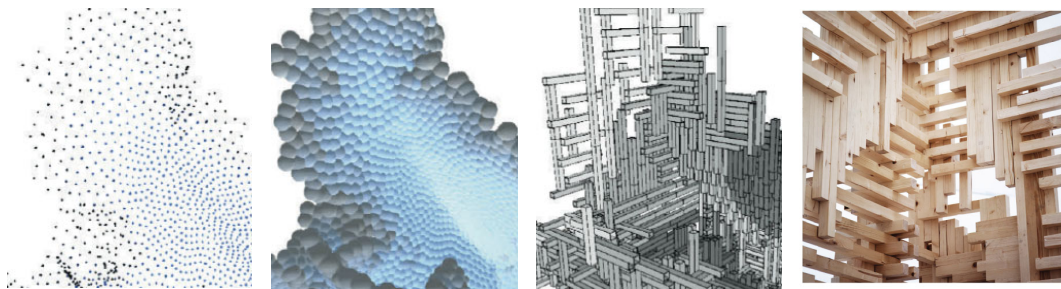


Figure 6. Timber structure discretization process adapted from Timber structure discretization process and component placement © U Cincinnati [51].

By developing componential designs that incorporate discretized principles from the outset and by using computational design and fabrication to ensure precision, quality, and resource efficiency, new approaches in architecture and building construction are in progress of being established [53]. The challenge remains to scale up, as most structures developed so far remain at the scale of pavilions.

Considering full-scale applications, robotic timber construction presents many theoretical, practical, and methodological challenges. For instance, it requires advanced computational design tools and novel constructive systems for automated construction processes, employing robust robotic fabrication technologies. In order to develop an approach for addressing these challenges, ETH Zurich started an in-depth investigation into robotic assembly of complex timber structures [9]. It explored novel esthetics and fabrication concepts enabled by digital technologies [54], while others increasingly incorporated structural performance [55]. Also, investigations into alternative structural systems, such as reciprocal structures [56] and folded structures [57], all demonstrate the potential that emerges at the intersection of computational design and robotic construction.

Discrete architectural design involves two main aspects, the design of the parts and the combinatorial design of the parts. The robotic production and assembly of the parts is informed by the combinatorial design, which relies on geometric interlocking, overlapping,

intertwining of the parts to create larger structures [58] with gaps < 1 mm ‘considerably compromised’ when force torque limits are reached [59].

The feedback loop established between the design directly and toolpath generation and sequencing are facilitating both prefabricated and on-site assembly workflows. These can be extended from assembly to include disassembly and reassembly [60,61] to create components that can be configured and reconfigured in various ways.

Discrete timber architecture contributes to a more sustainable, efficient, and adaptable construction paradigm by advancing modularity, scalability, and material efficiency. When combined with a circular design approach increased reduction in environmental impact is expected [62,63]. Hence, the value of discrete timber construction extends integrating design with real-time robotic feedback, semantic encoding, and circular lifecycle strategies, thus bridging the gap between computational logic and environmental ethics in robotic timber construction.

2.5. Circular Timber Architecture

Circular design is gaining momentum in robotic timber construction as the industry strives to reduce waste, optimize material usage, and minimize environmental impact. In particular, design-to-disassembly workflows using virgin or reclaimed wood with reversible connectors [64], material passports/part IDs, and reported reuse or life cycle assessment indicators (e.g., waste reduction, CO₂ emissions), rather than material choice alone [65]. These rely on advanced robotic systems to identify joints, dismantle components, and segregate materials for recycling or repurposing, ensuring minimal waste [66]. In prefabrication contexts, circular workflows have been shown to cut construction-stage waste to <5% (vs. 10–15% conventional), while robotic pipelines demonstrate complete component-level reuse in lab-scale re-prefabrication trials. CV is employed to identify defects in reclaimed wood with the goal to demarcate and remove them in order to ensure the structural integrity of the to-be-built structure [29]. The defect recognition using images of wooden boards relies on a trained model that identified the size of the board and demarcated the defects (Figure 7). However, the field still lacks a broader library of techniques and data frameworks to assess the embodied energy and reuse potential of timber components. Emerging work by [67] addresses robotic disassembly and structural reuse, but these remain at early TRL. Integrating real-time scanning, AI-based material classification, and circular lifecycle planning tools is essential to move beyond proof-of-concept. As a result, circularity in robotic timber construction remains both a technical and epistemic challenge—one that requires deeper collaboration between robotics, architecture, and lifecycle assessment.

2.6. Digital Intelligence for Robotic Timber Construction

Advances in AI, digital twins, multi-agent coordination, and immersive augmented and virtual reality (AR/VR) systems are expanding the scope of robotic timber construction [68]. These technologies are critical to enhancing adaptability, precision, and user–machine collaboration across the entire pipeline from design through fabrication to on-site assembly.

AR/VR play an increasingly important role in hybrid workflows, enabling intuitive human–robot interaction and real-time feedback. For instance, the Cooperative Augmented Assembly (CAA) system employs a phone-based AR interface to help users visualize sequences, allocate tasks between humans and robots, and adapt assembly steps under variable site conditions [69]. Similarly, immersive AR-assisted strategies that employ head-mounted displays and marker tracking can overlay virtual geometries on physical CLT elements, allowing non-expert builders to follow precise alignment cues [70]. These

technologies function as interactive layers between computational models and site realities, reducing uncertainty in part fitting, correcting misalignments, and enhancing precision in robotic timber projects.

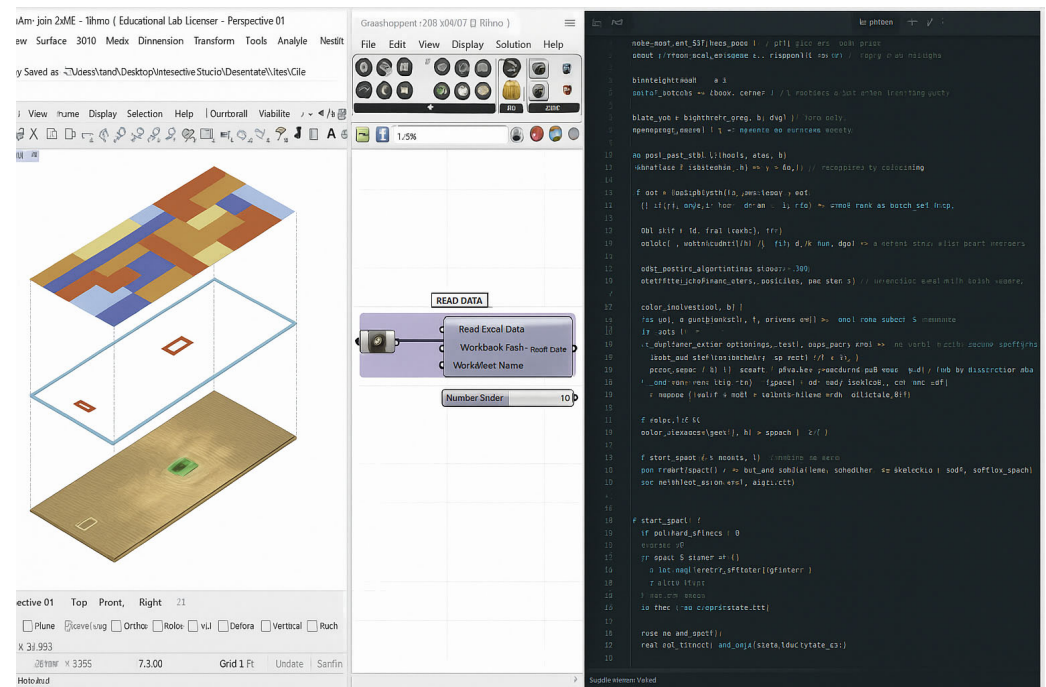


Figure 7. Computer vision identifies defects in reclaimed wood © TU Delft [29].

Furthermore, digital twin (DT) frameworks extend this integration by creating dynamic digital replicas of physical entities such as timber elements and robotic setups. Scanning locally sourced timber stock, for example, can feed into digital models that update robotic plans in response to material irregularities, thus improving utilization and joint accuracy [71]. Beyond individual case studies, DT-based workflows link material scans, process simulations, and feedback loops, showing potential to not only reduce off-cuts but also to enhance sustainability and lifecycle monitoring [72].

Multi-agent and collaborative robotics represent another frontier. Multi-agent systems (MAS) emphasize decentralized or partially decentralized coordination among multiple actors—robots, humans, or software agents—who follow local rules while achieving global assembly goals [73]. Recent research demonstrates distributed robotic teams capable of collaborative timber assembly, with algorithms that handle task planning, sequencing, and error recovery across multiple units [74]. MAS promise higher throughput and flexibility by enabling robots to work in parallel, cooperate on heavy or complex assemblies, and coordinate logistics, but they also introduce challenges of cost, synchronization, and communication overhead.

Overall, digital intelligence is enabling robotic timber construction to move beyond scripted prefabrication pipelines toward adaptive, feedback-rich ecosystems. AR/VR bridges design intent and site conditions; DT synchronizes material and robotic data for dynamic adjustments; and MAS distribute tasks across teams of robots and humans. Although these methods remain in experimental stages, they represent essential pathways for scaling robotic timber construction into resilient, circular, and industrially viable systems.

3. Methodology

To systematically map recent research developments and inform the selection criteria for the comparative analysis of robotic timber construction, a bibliometric approach was employed.

3.1. Data Source and Methods

The presented research utilized Scopus due to its comprehensive coverage of publications on engineering and its export tools for bibliometrics. Two windows were analyzed: (i) 2014–2025 to visualize long-term growth of timber–architecture vs. robotic–timber subsets; (ii) 2020–2025 for keyword co-occurrence, aligning with the recent acceleration of AI/HRI methods. Searches were executed in 2025. The following steps of data collection are listed:

1. Literature Search and Data Collection: A structured literature search was conducted in Scopus using the query: TITLE-ABS-KEY (timber OR wood OR “cross laminated timber” OR CLT) AND TITLE-ABS-KEY (robot* OR robotic OR cobot OR human–robot OR automation OR construction) with exploratory filters (prefabrication, assembly, discrete, circular).
2. Inclusion and Exclusion Criteria: Only English-language, peer-reviewed journal articles and conference papers within the fields of architecture, engineering, and robotics were considered. Publications focusing exclusively on forestry, agricultural robotics, or materials science unrelated to construction were excluded. Duplicate records were removed.
3. Keyword Processing: Author-provided keywords were lemmatized, and close variants were merged (e.g., human–robot collaboration/human robot collaboration; digital fabrication/robotic fabrication) to ensure consistency across the dataset.

3.2. Bibliometric Analysis

It has been identified that the annual number of relevant publications from Scopus rose from 2014 to 2024 (Figure 8). The broader field of Timber Architecture fluctuated between 30 and 80 items per year. Robotic Timber Construction showed steadier growth, increasing from about 10 items in 2014 to about 21 in 2024, with clear step-ups in 2019 and 2021. This robotics subset totaled 166 items, which is about 23% of the combined corpus. Taken together, the pattern indicates sustained expansion of robotics in timber construction, with an average growth rate in the range of 7 to 8 percent over the decade.

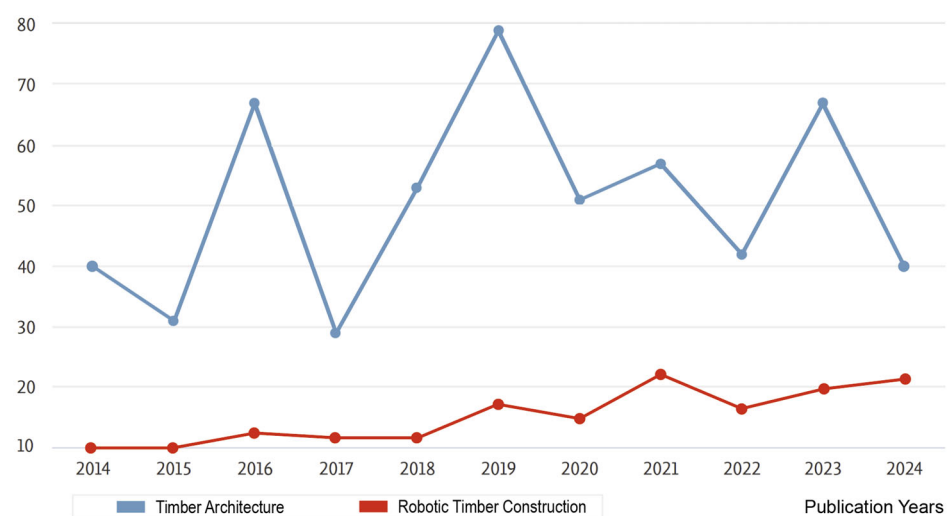


Figure 8. The progression of research papers using robotic technology in timber architecture.

To identify keyword co-occurrence, a network map was generated using VOSviewer (version 1.6.20), based on bibliographic data from 132 peer-reviewed publications (2020–2025) retrieved from the Scopus database (Figure 9). The analysis applied full counting, with a minimum threshold of three keyword occurrences. Default clustering settings were used and overlay visualizations mapped the temporal evolution of research focus based on average publication year. This was implemented to identify dominant and emerging thematic areas, with node size corresponding to keyword occurrence frequency, and linkages indicating keyword co-occurrence strength. Additionally, the color gradient illustrates temporal shifts in research focus, ranging from established core themes (e.g., robotic fabrication, architectural design) to emerging interests (e.g., digital twin, mixed reality, circular economy, human–robot collaboration).

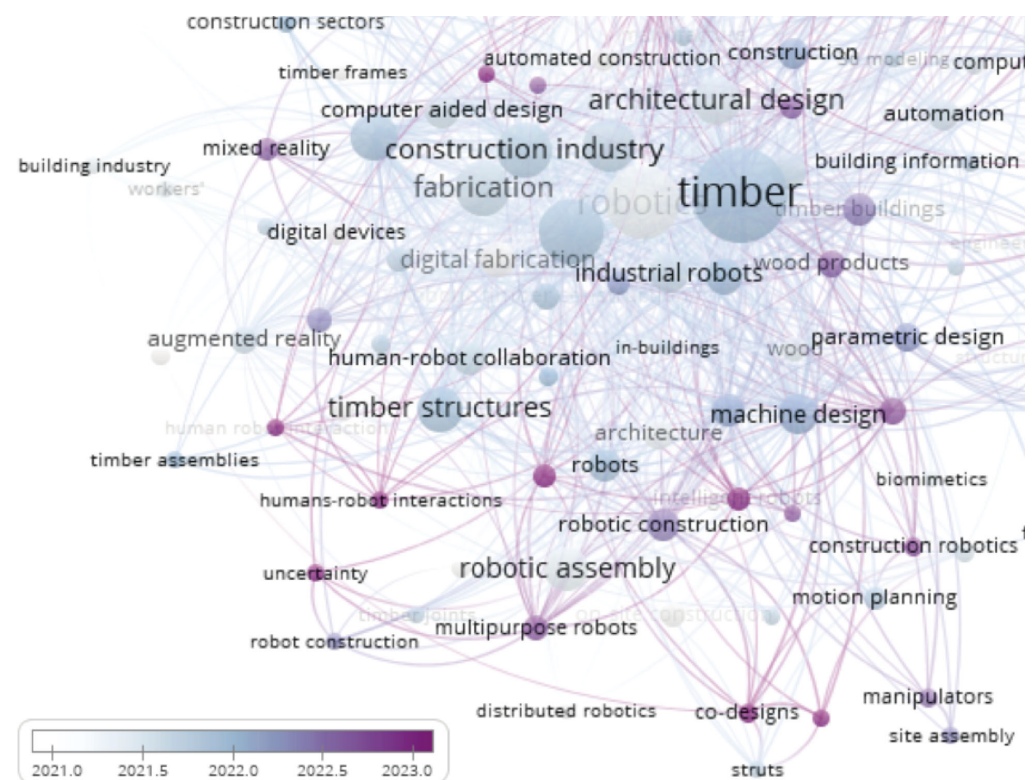


Figure 9. Keyword co-occurrence network of robotic timber construction research (2020–2025, Scopus, 132 publications). Node size indicates frequency of keyword occurrence and colors presents thematic clusters with overlay gradient indicating average publication year, highlighting established vs. emerging topics.

Between 2020 and 2025, robotic timber construction publications were dominated by industrial articulated arms, accounting for an average of 82.4% of the literature (Figure 10). Their share remained consistently high each year, indicating the field's ongoing reliance on fixed, factory-based robotic platforms. Cobot/HRI systems represented about 5.8%, appearing intermittently from 2020 onward in hybrid workflows combining human adaptability with robotic precision. Mobile manipulators (4.3%) emerged after 2023, reflecting growing experimentation with autonomous or semi-autonomous on-site assembly. Multi-robot systems (4.6%) appeared sporadically until 2025, when they reached their peak share, suggesting heightened interest in coordinated, distributed construction methods. The multi-agent category (2.9%) covered studies using decentralized, agent-based control frameworks, often in simulation or early-stage prototypes. Overall, while articulated arms still dominate, the gradual rise in mobile, collaborative, and multi-agent approaches indicates a slow but steady diversification of robotic platforms in timber construction research.

However, keyword co-occurrence and clustering are sensitive to author-provided keywords and normalization choices; hence, theme boundaries should be interpreted as indicative rather than definitive.

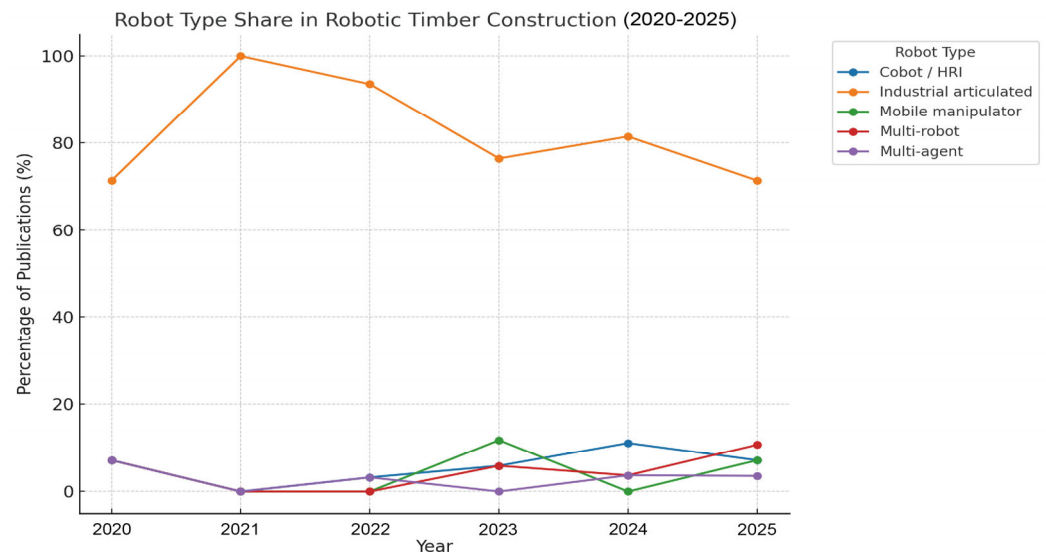


Figure 10. Annual distribution of robotic timber construction research by platform type (2020–2025, Scopus dataset). Categories include articulated arms, cobots/HRI, mobile manipulators, multi-robot systems, and agent-based control frameworks.

Based on these analysis various categories were identified and used in the Comparative Analysis Table (Table 1). Categories such as robotic technique, AI integration, TRL, HRI, and environmental metrics were defined explicitly in response to observable research trends and gaps identified through keyword clustering. Thus, the comparative analysis not only benchmarks selected case studies but also critically aligns with contemporary and emergent research trajectories, offering a robust, data-informed synthesis of current practices in robotic timber construction.

3.3. Comparative Analysis

The comparative analysis approach aims to evaluate the state-of-the-art advances in robotic timber construction in the period between 2020 and 2025. A curated set of twelve case studies was selected to reflect a broad spectrum of technological readiness levels (TRLs), artificial intelligence (AI) integration strategies, human–robot interaction (HRI) complexity, lifecycle stages, and material systems. The cases encompass academic explorations, experimental installations, and fully deployed industrial applications. The case selection focused on projects that meet four of the following characteristics:

- (1) Integration of AI-driven design, optimization, or decision-making tools
- (2) Application of robotic or automated techniques to timber assembly
- (3) Demonstrated lifecycle relevance (design, fabrication, and/or assembly) and contribution to circular economy and therefore sustainable construction
- (4) Technological readiness with physical prototyping or deployment evidence

Projects were chosen from the peer-reviewed academic literature, experimental research outputs, and validated field applications. Preference was given to cases that include detailed documentation of their methodology and platform architecture.

3.4. Data Source and Tools

To assess the maturity and real-world applicability of robotic timber construction systems, TRL classification spanning from 1 (basic research) to 9 (industry deployment),

bridging academic innovation and industrial implementation is employed. Each reviewed project was positioned along the TRL spectrum based on the extent of prototype validation, field deployment, and operational feedback.

Primary data was extracted from peer-reviewed academic journals (e.g., *Automation in Construction*, *Frontiers in Robotics and AI*), institutional white papers, and documented project reports. Supplementary data, including implementation status and system performance, was cross-verified using institutional repositories and public online datasets. Structured tables created in Microsoft Word and Excel compiled technical parameters, system typologies, and deployment scales. TRL estimation was complemented by an AI integration scale that categorized implementation into limited, moderate, or extensive use, based on the complexity and role of AI within the robotic pipeline. These categories represent limited scripted/parametric only; moderate, single-stage learning/optimization; and extensive multi-stage perception-and-planning and/or DT-linked feedback). HRI Level is encoded as none/assisted/collaborative; DT is marked only when explicitly used for simulation/QA/synchronization.

Following tabulation, a pattern analysis was conducted to identify

- Recurring technical and design strategies (e.g., discrete modularity, DT integration);
- Novel AI integrations (e.g., reinforcement learning, agent-based modeling);
- Emergent typologies of robotic timber systems;
- Underrepresented areas (e.g., multi-agent swarms).

The insights drawn from this methodology directly inform the discussion and conclusion sections of the paper, outlining not only the current state of the field but also strategic gaps and future directions for research and implementation.

3.5. Comparative Analysis Table

To bridge the bibliometric findings and the subsequent comparative discussion, this section summarizes the key characteristics of the reviewed studies. Table 1 compiles the major research dimensions—including robotic methods, AI integration, human–robot interaction, TRL, and sustainability aspects—identified through the literature mapping and data extraction. It provides an overview that supports the comparative evaluation presented in Section 4.

Table 1. Comparative analysis table for the scientific literature on robotic timber construction (2020–2025, 12 cases). The cases are normalized across six fields: (1) technical approach; (2) digital intelligence (AI/HRI/DT); (3) TRL; (4) lifecycle stage; (5) materials; and (6) sustainability outcomes. Abbreviations for AI level are L/M/E, standing for limited, moderate, and extensive; for HRI, –/A/C stand for none/assisted/collaborative; and for lifecycle, D/P/O/M stand for design/prefab/on-site/mixed.

Study/Platform	Robotic Technique	Digital Intelligence (AI/HRI/DT)	TRL	Lifecycle/Materials	Sustainability
Apolinarska et al., 2020 [55]	Reversible robotic timber assembly	L/A/– (parametric adaptation)	4	P/engineered timber	Reusability and flexible connections
Bier et al., 2024 [29]	Robotic milling and 3D printing with reused wood	M/C/– (CV, ML cutting optimization)	6	P/reclaimed wood + sawdust biopolymer	Full CE loop, CO ₂ reduction, local sourcing
Chai et al., 2022 [40]	Mobile robotic assembly	M/–/– (computational design)	7	O/CLT	Reduced construction waste
Claypool et al., 2020 [60]	Robotic modular Assembly	E/–/DT (generative design, AR/VR, DT)	8	M/plywood, engineered timber	Reusable modules, reduced emissions, circular reuse logic

Table 1. Cont.

Study/Platform	Robotic Technique	Digital Intelligence (AI/HRI/DT)	TRL	Lifecycle/Materials	Sustainability
Apolinarska et al., 2020 [55]	Reversible robotic timber assembly	L/A/– (parametric adaptation)	4	P/engineered timber	Reusability and flexible connections
Kunic et al., 2021 [75]	Robotic timber truss assembly	M/–/DT (motion planning)	5	P/engineered timber	Adaptive truss assembly, high flexibility
Larsen et al., 2022 [76]	Curved oak timber fab	M/–/– (natural form optimization)	6	P/naturally curved timber	Natural form utilization and waste reduction
Lauer et al., 2023 [11]	Automated on-site assembly	E/–/– (biomimetic algorithms)	7	O/engineered timber	Efficient material usage
Leder & Menges, 2024 [77]	Collective robotic construction with ABM	E/–/DT (ABM, DT sync)	5–6	M/spruce struts	Real-time robotic adaptation
Reisach et al., 2024 [66]	Digital circular timber fabrication	L/–/– (circular design optimization)	7	P/reclaimed timber	Circular economy integration
Restin, 2020 [15]	Discrete timber assembly	L-M/–/– (discrete construction algorithms)	6	M/engineered timber	Improved material efficiency
Rogeau et al., 2021 [47]	Robotic timber joint fabrication	M/–/– (integrated toolpath generation)	7	P/timber plates	Precision fabrication, waste minimization
Eduardo, 2023 [48]	AI-based timber optimization	M/–/– (ML + optimization)	6	P/natural timber	Minimized wood waste

3.6. Evaluation

The comparative analysis of 12 projects in robotic timber construction from 2020 to 2025 reveals a convergence of digital design systems, AI integration, and sustainable timber workflows. These projects collectively showcase a multi-dimensional evolution in construction practices that include computational logic, robotic assembly, and circular strategies. Several key themes emerge:

- Discrete Modularity: Across nearly all case studies, discrete timber units (e.g., blocks, joints, trusses) form the basis of robotic workflows. This modularity facilitates prefabrication, automation, and reuse.
- AI: From object detection (YOLOv5) and component layout optimization to reinforcement learning in joint assembly and agent-based modeling for construction choreography, AI methods are employed at various scales.
- Circularity: In recent studies (e.g., [29,60]), timber reuse and environmental accountability are increasingly central, suggesting future frameworks will integrate lifecycle data from the outset.
- Human–Machine Collaboration: Several projects ([60,75,77]) highlight hybrid intelligence, where humans intervene within digital twins or augmented interfaces. These interfaces are no longer passive but constitute co-creative systems.
- Real-time and Distributed Robotics: Studies by [40,77] push beyond pre-programmed sequences, introducing responsive and multi-agent strategies that adapt to environment, errors, and progress.

These themes highlight how robotic timber construction is no longer confined to prefabrication automation or isolated robotic arms. Instead, the field is evolving toward in-

tegrated, adaptive ecosystems where computation, material feedback, and AI are mutually reinforcing each other.

3.7. Synthesis and Implications

Reading the twelve cases side by side reveals consistent patterns that go beyond individual demonstrations:

- (1) Discrete modularity is the common denominator and a readiness enabler.

Almost every project adopts discrete timber units (blocks, joints, trusses, struts). Projects that standardize part families and connection grammars progress to higher TRLs and are easier to adapt for circularity (reversible joints, module reuse). Implication: Discrete design rules are not just esthetic; they are a precondition for repeatable automation and for end-of-life disassembly.

- (2) AI's role diverges by lifecycle stage.

Factory/prefab projects mainly use AI for optimization (cut layout, nesting, parametric/ML optimization), while on-site projects that face uncertainty use perception and planning (CV, DT synchronization, ABM) to update actions in real time.

- (3) Hybrid HRI is the operational default on site.

Fully automated sequences dominate in factory settings, but on-site projects involve assisted/cooperative HRI (human task framing, teaching, recovery from errors).

- (4) Circularity is present but rarely quantified.

Several cases document reversibility, material fit, waste reduction, or closed loops, yet only a minority report normalized metrics (e.g., CO₂ equivalent or % reuse). Field adoption would benefit from shared assessment templates that pair robotic data (toolpaths, offcuts) with LCA indicators.

- (5) DTs are pivotal when coupled with multi-agent logic.

Where DTs are used as passive viewers, they have limited impact. Cases that synchronize DTs with agent-based controllers or task-level planning (e.g., Leder & Menges) show responsive and distributed behaviors (re-planning, error recovery). Hence, value comes from closing the loop between simulation and control, not from visualization alone.

- (6) Tool chain fragmentation is a barrier to scale.

Most workflows rely on bespoke parametric scripts and ad hoc robot control. This increases integration effort and narrows the pool of trained operators. Hence, priority should be given to open interfaces (ROS/URDF, IFC-based DfMA schemas) and interoperable grammars for joints and sequences.

4. Challenges and Opportunities

This review identifies opportunities in robotic timber construction driven by advances in automation, prefabrication, discrete design methods, and circular economy principles. Yet, several significant challenges still need consideration. For instance, scaling from small-scale prototypes to large-scale industrial applications. Achieving scalable solutions requires sophisticated frameworks for handling real-world uncertainties. Taking the next step involves not only understanding which tasks can be fully automated vs. HRI-supported but also identifying sequences of tasks. There are two main aspects to consider:

- (a) Advanced closed-loop design to construction requires identifying and advancing computational tools and AI-supported design to robotic materialization processes

of full-scale discrete architecture. The overall goal is to leverage AI and computational tools to explore vast design spaces, customizable solutions, and their potential for scalability.

- (b) Scalability addressing the disparity between the scale of robotic setups and the scale of buildings remains a significant challenge to address. From digital design to prefabrication and on-site assembly, a parametric design process and automated fabrication data generation are required to adapt a construction system and its building parts to specific structural or architectural requirements.

In this context, the potential of AI is in the combinatorics of discrete timber elements, constrained by robotic assembly, which can be explored through advanced simulation tools such as NVIDIA Omniverse and robotic development simulators like Isaac. These platforms simulate real-world physics and synthesize complex workflows. Once encoded, computational fabric based on data from the robotic assembly of discrete elements and their joints can be deployed in generative design sequences, unlocking new design potentials for prefabricated architecture. AI-driven combinatorics can expand the variability of discrete timber prefabrication by exploring large design spaces and enabling generative sequencing of elements. Case studies show that discrete automation and digital twin optimization can reduce waste, improve log-to-board utilization, and lower rework rates in specific contexts. While these suggest potential carbon and cost benefits, systematic evidence is still limited and largely project-specific; therefore, broader validation with benchmark tasks and lifecycle metrics remains a key research need.

Realizing these opportunities demands stronger interdisciplinary collaboration across architecture, robotics, structural engineering, and sustainability domains. By addressing these challenges, robotic timber construction can evolve toward scalable, adaptive, and genuinely circular construction practices, reshaping the future of architectural production.

5. Discussion

The review highlights that robotic timber construction is no longer limited to isolated laboratory experiments but is gradually evolving toward integrated, adaptive, and circular workflows. Still, critical reflection shows that the field remains at a crossroads between technological promises and systemic barriers.

First, while advances in discrete design, digital twins, and AI-driven combinatorics reveal powerful new workflows, these systems often remain project-specific. There is limited evidence that results translate consistently across contexts, materials, and scales. Without comparative benchmarks and shared datasets, it remains difficult to evaluate whether robotic approaches genuinely outperform conventional prefabrication in terms of cost, reliability, or carbon impact.

Second, the gap between research and practice remains significant. Many projects rely on bespoke pipelines, one-off robotic setups, or high levels of manual supervision. This raises questions about whether current methods are scalable in industry, or whether they risk remaining confined to academic demonstrators. Developing open interfaces and standardized modules may help, but adoption will depend on clear evidence of economic and environmental value.

Third, the integration of robotics into timber construction requires rethinking labor and expertise. The promise of human–robot collaboration is frequently noted, yet questions about socio-technical implications in terms of who supervises these systems and how do new roles intersect with existing construction trades still need definition. Without structured training and professional certification, robotic timber construction risks creating knowledge bottlenecks that limit adoption rather than accelerate it.

Fourth, although many studies frame robotic timber as an enabler of circularity and sustainability, this assumption requires more critical validation. Robotic disassembly and reuse workflows remain low-TRL, and timber's performance in long-term reuse cycles (especially when combined with adhesives, coatings, or hybrid materials) is still underexplored. Life-cycle analyses, if systematically applied, may reveal trade-offs that challenge optimistic assumptions about waste reduction.

Finally, the field faces a vision dilemma regarding prioritizing robotic timber construction efficiency and automation within existing building practices, or aiming for new architectural paradigms (e.g., discrete, reconfigurable systems). Current evidence suggests that both directions are being pursued simultaneously. A more explicit debate on priorities could help consolidate the field and guide investments toward the most impactful pathways.

Hence, the promise of robotic timber construction lies not only in technical advances but also in the ability to build robust interdisciplinary collaborations, foster integrative expertise, and critically assess the real-world implications of automation. Without addressing these challenges, the field risks technological stagnation or limited niche adoption; with them, it could become a central driver of sustainable and adaptive building practice.

6. Conclusions

This paper has critically reviewed recent advancements in robotic timber construction, highlighting notable progress in automation, AI integration, discrete architecture, and circular construction practices. The comparative analysis of key projects from 2020 to 2025 underscores the evolution toward increasingly intelligent and adaptive construction paradigms. However, persistent challenges remain such as scalability issues, incomplete lifecycle integration, and the absence of consistent industrial pathways.

Emerging solutions such as DTs, AI-driven real-time adaptation, advanced combinatorial simulation, and circular economy frameworks offer promising avenues to address these gaps. Future research should focus on embedding semantic intelligence into discrete modular systems, developing robust multi-agent robotic ecosystems, and enhancing AI-HRI collaboration in design-to-construction workflows. Scaling robotic timber construction from proof-of-concept experiments to industry-wide adoption will require solutions that integrate design, fabrication, and assembly processes while also addressing unpredictable site conditions, wireless communication limitations, and workforce capacity. Success depends on close collaboration between technology developers, construction firms, policymakers, and educational institutions to create adaptable, efficient, and cost-effective pathways to industrial deployment. To clarify the main findings and implications of this review, the following themes can be highlighted:

- Technological readiness: Current systems remain largely mid-TRL and require validation in real-world, full-scale projects.
- Scalability: Transitioning from lab-scale prototypes to building applications demands tolerance management, logistics coordination, and robust frameworks for uncertainty.
- Regulation and safety: Clear standards for HRI, liability frameworks, and occupational safety protocols are essential for industrial deployment.
- Cost and productivity: Transparent benchmarks—covering cycle times, rework rates, embodied carbon, and lifecycle cost—are needed to demonstrate economic viability.
- Workforce training: Targeted curricula and micro-credentials are necessary to prepare “robotic timber integrators” capable of bridging material knowledge and robotic workflows.
- Ecosystem and expertise: The lack of system integrators and standardized modules limits replication and scalability.

- Circularity: Robotic disassembly and reuse remain at low TRL; systematic studies on lifecycle benefits and performance are still missing.

Building on these findings, several areas for future research and development can be identified. A priority is to develop standardized benchmarks and datasets that allow rigorous comparison between robotic and conventional timber construction, covering performance, cost, and environmental metrics. At the same time, policy frameworks are needed to address occupational safety, liability, and certification of robotic workflows, ensuring that deployment at scale meets regulatory requirements. Parallel efforts should focus on expanding educational pathways and training programs to cultivate cross-disciplinary expertise that integrates timber craft, robotics, and AI. In addition, open interoperability standards linking BIM/CAD environments with robotic toolchains and lifecycle data will be essential for streamlining workflows and enabling reproducibility. Finally, large-scale demonstrators are required to validate circular practices such as robotic disassembly, structural reuse, and material passports, providing tangible evidence of feasibility and long-term value for industry adoption.

The presented study provides a systematic overview of robotic timber construction, integrating developments in automation, AI, discrete design, and circular strategies. It helps scholars gain a comprehensive understanding of technological readiness, regulatory barriers, and training needs in this domain. It also helps industry practitioners recognize the importance of cost evaluation, occupational safety, and workforce development in moving from prototypes to scalable industrial applications, thereby promoting sustainable and adaptive construction practices.

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