Review

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*Review*

# Review of Advances in the Robotization of Timber Construction

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**Abstract**

Robotic timber construction has advanced significantly in the last decade, considerably impacting production efficiency and sustainability. This paper explores via literature review the state-of-the-art robotization in timber construction by identifying various computational and robotic tools, techniques, and methods that support the design to fabrication process. It identifies through bibliometric analysis and comparative case study evaluations, emerging trends are identified, including the use of advanced artificial intelligence (AI) methods such as digital twins, real-time adaptive workflows, and machine learning-driven fabrication processes. It furthermore reflects on the advantages of robotic production and assembly, and the challenges to adopting these technologies at large scale. It contributes to understanding current level of robotization in timber construction and identifying future steps.

**Keywords:** timber construction; robotization; discrete and circular design; sustainability

## 1. Introduction

The building construction industry is responsible for high carbon emissions, significant resource waste, and persistently low production efficiency[1]. With the rise in carbon dioxide emissions acknowledged as the primary driver of climate change, a shift in the construction industry to-wards more sustainable practices and the use of renewable materials is increasingly implemented [2]. 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 [3].

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 [4]. Various applications show considerable levels of automation. Automated prefabrication of timber components has demonstrated substantial advantages that enhance the overall construction process while significantly improving the efficiency, quality, and sustainability of construction projects [5], [6], [7].

By integrating advanced automation into design, fabrication, and assembly processes, robotic timber construction addresses critical challenges in material efficiency, labor productivity, and sustainability [8]. 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 [9], [10].

In recent years, discrete automation using robotics, AI, and industrial automation systems optimize manufacturing processes that involve discrete elements [11]. Such scalable approach to computational design and manufacturing facilitates mass production of self-similar elements. Main consideration is that robotized vs. conventional computer-numerically controlled (CNC) approaches are (a) more capable of handling complex geometries [12] due to their multiple degrees of freedom, allowing them 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.

This paper discusses advancements of automated technologies in the timber construction industry, focusing on the design-fabrication-assembly methods and addressing their scalability for industry adoption. Specifically, it explores material handling, joinery, on-site and off-site assembly, and AI-assisted workflows from design to construction.

## 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[1] 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 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 [13]. 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 © ETH Zurich [14].

Against this backdrop, robotic timber construction is rapidly maturing and nearing technology readiness level for large-scale implementation [14]. 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. Automation

Knowing that about 50% of all tasks can be automated, while 45% are Human-Robot Interaction (HRI) supported and 5% remain in human hands[2], identifying what tasks can be fully automated vs. HRI-supported requires examining the various tasks that robots can perform. Automating existing

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[1] Link to UNECE report: https://unece.org/sites/default/files/2023-05/ECE_TIM_DP95E_web.pdf

[2] Link to McKinsey report: https://www.mckinsey.com/featured-insights/themes/how-automation-is-shaping-the-future-of-work

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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 in place, and release). 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 [15]. 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 [17].

This HRI-supported approach involves two main aspects, the design of the parts, i.e. building com-ponents, and the design of the assembly based on the robotic production and assembly constraints. The robotic assembly relies on automated and Human-Robot Interaction (HRI) -supported processes that requires 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 [18].

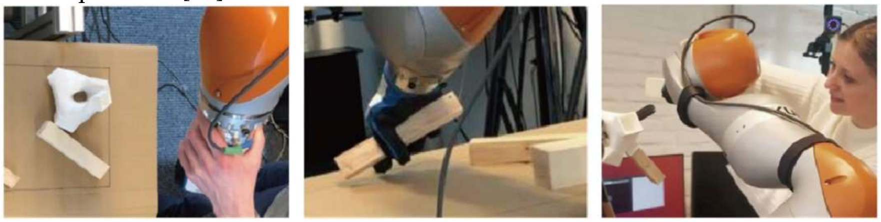

**Figure 2.** CV and HRI assembly of scaled prototype © TU Delft [17].

Depending on the project, a combination of automated and HRI-supported on- and off-site fabrication processes is implemented.

### *2.2. Prefabrication*

Automated prefabrication of timber elements has been demonstrated in various research studies and projects in the last decades [19], [20], 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 [21]. Prefabrication systems draw upon concepts of reconfigurable factories, agile production networks, and decentralized manufacturing (Figure 3), designed to rapidly adapt to evolving market demands. Furthermore, studies have shown that prefabrication can reduce greenhouse gas emissions, energy use, and construction waste, contributing to a lower environmental footprint [22]. The resulting decrease in the environmental footprint further underscores the transformative potential of automated prefabrication in timber construction [23].

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**Figure 3.** Pre-assembly timber structure (left) and the on-site assembly of large components (right) © University of Stuttgart [16].

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.

*2.3. On-Site Construction*

Automated on-site construction involves to some degree HRI, 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 [24]. 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 [7], [25].

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 [26] and intuitive design to fabrication processes [27]. These applications simulate site operations, allowing for detailed previsualization, real-time adjustments, and improved coordination between human operators and robotic systems.

Currently, on-site robotic construction mainly focuses on additive manufacturing (AM), automated installation systems, and robotic assembly systems [28]. 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 im-pact discrete architecture.

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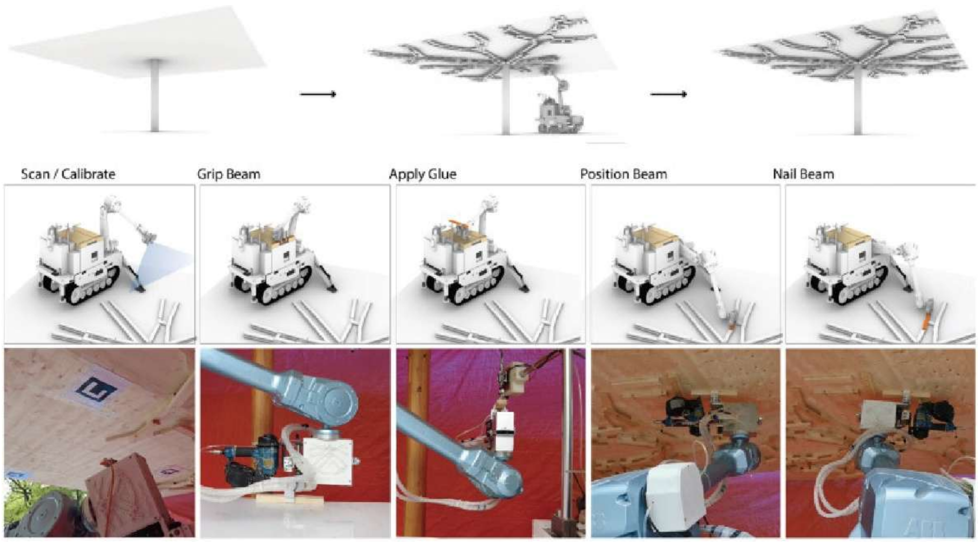


**Figure 4.** On-site fabrication scenario repeating workflow of five routines, scan, pick, glue, place, nail beam process © U Tongji [7], [25].

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 [29]. For instance, École Polytechnique Fédérale de Lausanne (EPFL) developed integrated design tools for timber plate structures (Figure 5). 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 [30], [31].

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 [32]. Demonstrating superior performance in path optimization, reduced material waste by 17% compared to conventional CNC machining manufacture in mortise and tenon structures [33].

The continuous workflow ranging from computational design, to optimization, and robotic fabrication requires developing an understanding of the discrete architecture approach.

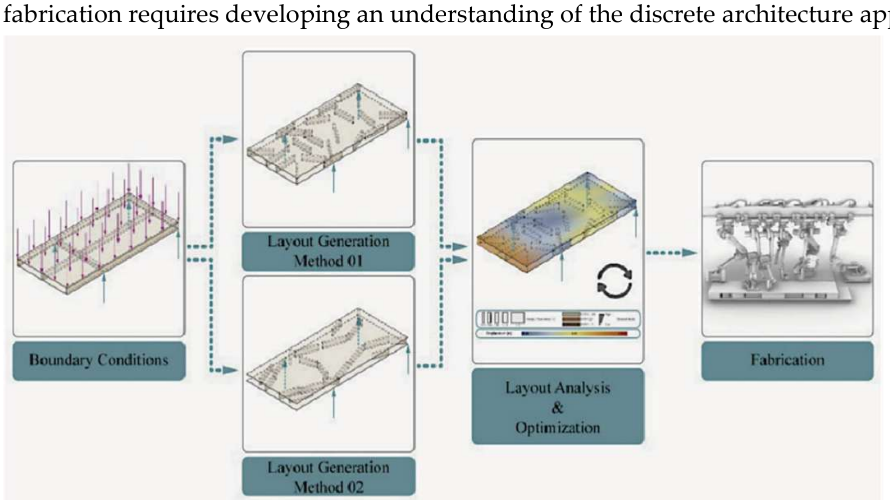


**Figure 5.** Continuous workflow of computational design, optimization, and robotic fabrication steps for constructing planar timber slabs © EPFL.

*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 discrete generative design 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 [34].

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 [35]. 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 [5]. It explored novel aesthetics and fabrication concepts enabled by digital technologies [36], while others increasingly incorporated structural performance [37]. Also, investigations into alternative structural systems, such as reciprocal structures [38] and folded structures [39], all demonstrate the potential that emerges at the intersection of computational design and robotic construction.

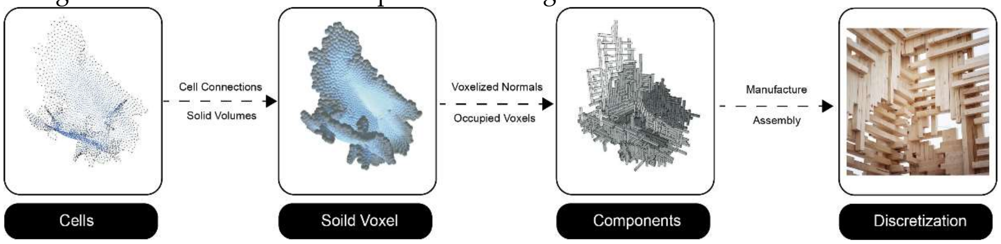


**Figure 6.** Timber structure discretization process and component placement. Adapted from *Timber structure discretization process and component placement* © U Cincinnati [34].

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 [40]. 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 [41], [42] 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 of environmental impact is expected [43], [44]. 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. For instance, advanced robotic systems identify joints, dismantle components, and segregate materials for recycling or repurposing, ensuring minimal waste [45]. 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 [18]. The defect recognition using images of wooden boards relies on a trained model

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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 [46] addresses robotic disassembly and structural reuse, but these remain at early TRL levels. 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.

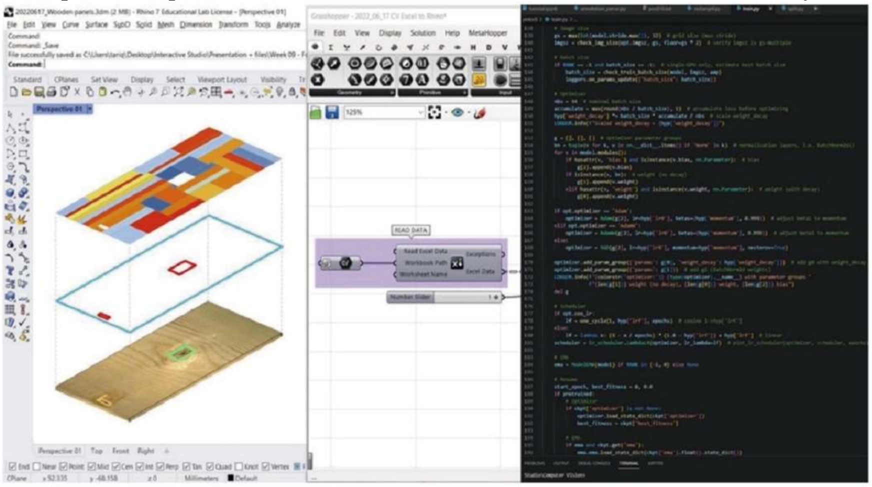

**Figure 7.** Computer Vision identifies defects in reclaimed wood © TU Delft [18].

## 3. Robotization of Timber Construction

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. Bibliometric Analysis*

As shown in Figure 8, the annual number of relevant publications from Scopus rises from 2014 to 2024 (556 items). The broader field of Timber Architecture fluctuates between 30 and 80 items per year. Robotic Timber Construction shows 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 totals 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.

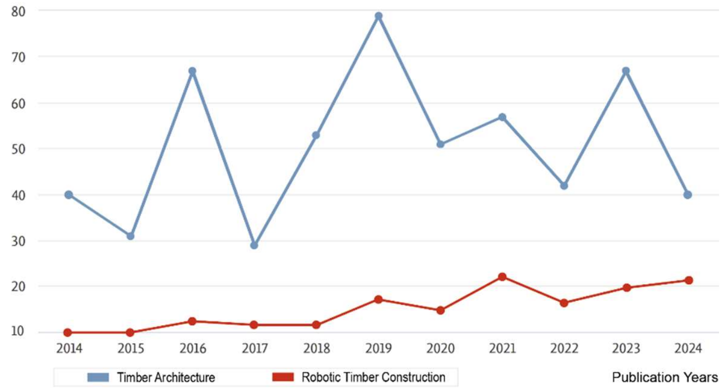


**Figure 8.** The progression of research papers using robotic technology in timber architecture.

To identify keyword co-occurrence a network map was generated using VOSviewer, based on bibliographic data from 132 peer-reviewed publications (2020–2025) retrieved from the Scopus database (Figure 9). 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).

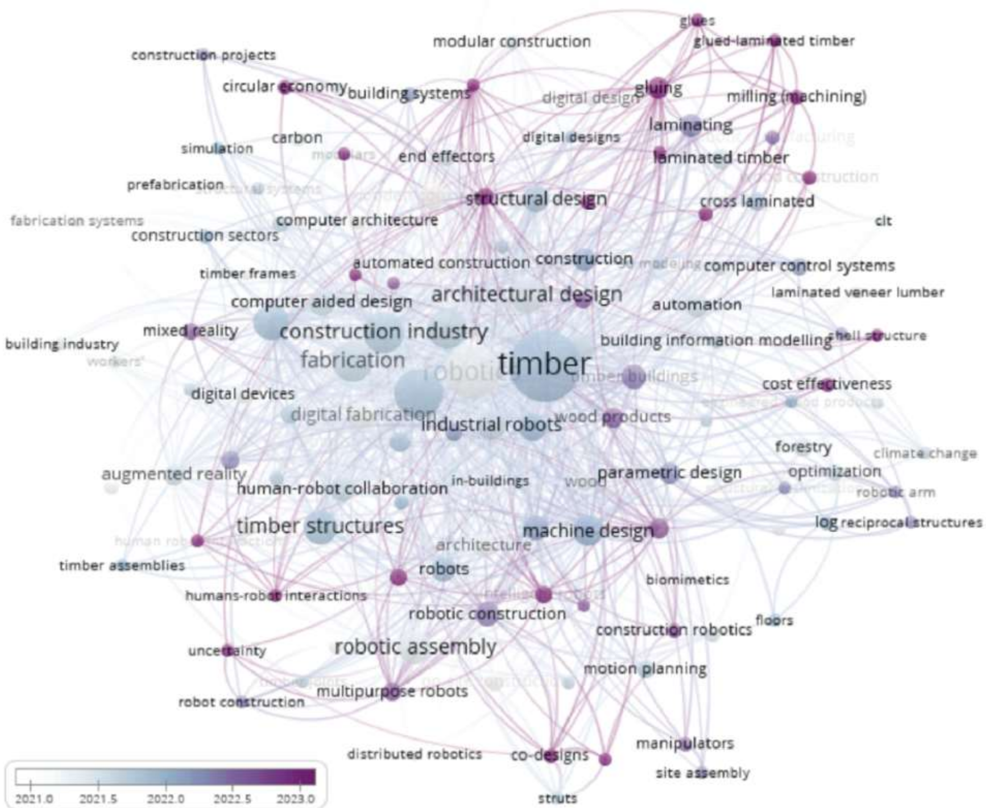


**Figure 9.** Visual Analysis of key research co-occurrence (2020-2025).

Second, between 2020 and 2025, robotic timber construction publications were dominated by industrial articulated arms, accounting for an average of 82.4% of the literature. 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 of mobile, collaborative, and multi-agent approaches indicates a slow but steady diversification of robotic platforms in timber construction research.

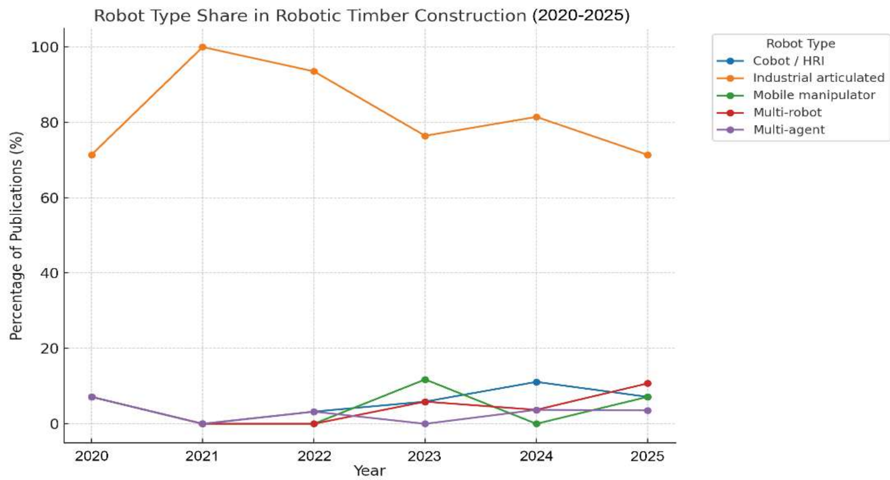


**Figure 10.** Temporal distribution of robot construction types based on surveyed studies.

Based on these analysis various categories were identified and used in the Comparative Analysis Table. Categories such as Robotic Technique, AI Integration, TRL and HRI Level, 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.

### *3.2. Comparative Analysis*

The comparative analysis approach aims to evaluate the state-of-the-art advances in robotic timber construction in the period between 2020 to 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 at least 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 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.

### *3.3. Data Source and Tools*

To assess the maturity and real-world applicability of robotic timber construction systems, we incorporated the Technology Readiness Level (TRL) framework as visualized in the diagram (Figure 9). This classification spans from TRL 1 (basic research) to TRL 9 (industry deployment), bridging academic innovation and industrial implementation. TRL assessments in this study were informed by standards defined by the European Union's Horizon program and NASA guidelines. Each reviewed project was positioned along the TRL spectrum based on the extent of prototype validation, field deployment, and operational feedback.

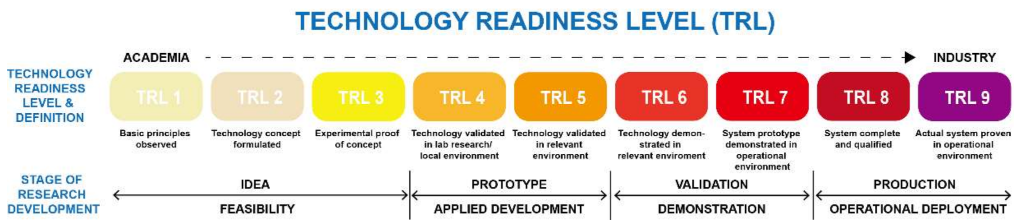


**Figure 9.** Technology Readiness Level (TRL) framework integration.

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.

Following tabulation, a pattern analysis was conducted to identify:

- Recurring technical and design strategies (e.g., discrete modularity, digital twin 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.

### *3.4. Comparative Analysis Table*

**Table 1.** Comparative analysis table for scientific literature on robotic timber construction (2020–2025, 12 cases).

| Study / Project | Robotic Technique | AI integration & Methodology | TRL | Lifecycle Stage | Materials Handled | Environmental Metrics | Software Used |
|---|---|---|---|---|---|---|---|
| **Apolinarska et al., 2020** | Reversible robotic timber assembly | Moderate (Parametric Adaptation Algorithms) | 4 | Prefab | Engineered timbers | Reusability and flexible connections | Parametric design & robot control software |
| **Bier et al., 2024 (TU Delft)** | Robotic milling & 3D printing with reused wood | Extensive (YOLOv5, ML cutting optimization) | 6 | Prefab | Reclaimed wood & sawdust biopolymer | Full CE loop, $CO_2$ reduction, local sourcing | Rhino, Grasshopper, YOLOv5 |
| **Chai et al., 2022** | Mobile robotic assembly | Extensive (computational design) | 7 | On-site | Cross-laminated timber | Reduced construction waste | Computational design tools & robotic control software |
| **Claypool et al., 2025** | Robotic modular Assembly | Extensive (Generative Design, In-browser AR/VR, Digital Twin) | 8 | Mixed | Plywood / engineered timber | Reusable modules, reduced emissions, circular reuse logic | Master Builder, browser-based CAD, Grasshopper |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Kunic et al., 2021** | Robotic timber truss assembly | Moderate (Digital Twin & Motion Planning) | 5 | Prefab | Engineered timber | Adaptive truss assembly, high flexibility | Digital twin simulation tools & robotic control software |
| **Larsen et al., 2022** | Curved oak timber fab | Moderate (Natural Form Optimization) | 6 | Prefab | Naturally curved timber | Natural form utilization & waste reduction | Parametric form-finding software |
| **Lauer et al., 2023** | Automated on-site assembly | Extensive (Biomimetic Algorithms) | 7 | On-site | Engineered Timber | Efficient material usage | Parametric form-finding software |
| **Leder & Menges, 2024** | Collective robotic construction with ABM | Extensive (Agent-Based Modelling, Digital Twin Sync) | 5-6 | Design, Simulation, Assembly | Spruce timber struts | Real-time robotic adaptation | ABM Framework, Rhino, Grasshopper, Visual Studio |
| **Reisach et al., 2024** | Digital circular timber fabrication | Moderate (Circular Design Optimization) | 7 | Prefab | Reclaimed timber | Circular economy integration | Circular economy software |
| **Restin, 2020** | Discrete timber assembly | Moderate (Discrete construction Algorithms) | 6 | Mixed | Engineered timber | Improved material efficiency | Discrete construction software |
| **Rogeau et al., 2021** | Robotic timber joint fabrication | Extensive (Integrated Toolpath Generation) | 7 | Prefab | Timber plates | Precision fabrication, waste minimization | Automated design software |
| **Eduardo, 2023** | AI-based timber optimization | Extensive (Machine Learning & Optimization) | 6 | Prefab | Natural timber | Minimized wood waste | AI optimization software |

*3.2. 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., Bier, AUAR) timber reuse and environmental accountability are increasingly central, suggesting future frameworks will integrate lifecycle data from the outset.

•Human–Machine Collaboration: Several projects (AUAR, Leder and Menges, Kunic) 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 Leder & Menges (2024) and Chai et al. (2022) 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 integrated, adaptive ecosystems where computation, material feedback, and AI are mutually reinforcing each other.

## 4. Challenges and Opportunities

The review identifies substantial 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 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, that 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 significantly increase the variability of timber prefabrication, achieve unprecedented variability while reduce the carbon footprint and construction costs, which is achieved by combining robotization for efficient mass production with circular principles.

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. Conclusions

This paper presets 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 towards increasingly intelligent and adaptive construction paradigms. However, critical synthesis reveals persistent challenges, notably scalability issues, and incomplete lifecycle integration.

Emerging technological solutions, such as digital twins, AI-driven real-time adaptation, advanced combinatorial simulation, and circular economy frameworks—present promising pathways to overcome current limitations. Further research will focus explicitly on embedding semantic intelligence within discrete modular systems, developing robust multi-agent robotic ecosystems, and leveraging AI and HRI for intuitive human–machine interactions in design-to-construction workflows.

Scaling robotic timber construction from proof-of-concept projects to industry-wide applications demands robust solutions for integrated design to construction processes. This includes overcoming limitations in wireless communication, handling of unpredictable site conditions, human skill building, etc. Addressing these challenges requires collaboration between technology developers, construction firms, policymakers, and educational institutions to create adaptable, efficient, and cost-effective solutions for robotic construction.

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**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. T. Bock, "The future of construction automation: Technological disruption and the upcoming ubiquity of robotics," *Automation in Construction*, vol. 59, pp. 113–121, Nov. 2015, doi: 10.1016/j.autcon.2015.07.022.
2. G. Concu, *Wood in Civil Engineering*. Rijeka: IntechOpen, 2017. doi: 10.5772/63178.
3. X. Shan *et al.*, "Wood for Application in Electrochemical Energy Storage Devices," *Cell Reports Physical Science*, vol. 2, no. 12, p. 100654, Dec. 2021, doi: 10.1016/j.xcrp.2021.100654.
4. S. Jeska and K. S. Pascha, *Emergent timber technologies: materials, structures, engineering, projects*. Basel Boston: Birkhäuser, 2015.
5. J. Willmann, F. Gramazio, and M. Kohler, "New paradigms of the automatic," in *Advancing Wood Architecture*, 1st ed., A. Menges, T. Schwinn, and O. D. Krieg, Eds., New York : Routledge, 2016.: Routledge, 2016, pp. 13–28. doi: 10.4324/9781315678825-2.
6. E. Lachance, N. Lehoux, and P. Blanchet, "Automated and robotized processes in the timber-frame prefabrication construction industry: A state of the art," in *2022 IEEE 6th International Conference on Logistics Operations Management (GOL)*, Strasbourg, France: IEEE, June 2022, pp. 1–10. doi: 10.1109/GOL53975.2022.9820541.
7. A. P. R. Lauer *et al.*, "Automated on-site assembly of timber buildings on the example of a biomimetic shell," *Automation in Construction*, vol. 156, p. 105118, Dec. 2023, doi: 10.1016/j.autcon.2023.105118.
8. R. Dindorf and P. Wos, "Challenges of Robotic Technology in Sustainable Construction Practice," *Sustainability*, vol. 16, no. 13, p. 5500, June 2024, doi: 10.3390/su16135500.
9. N. Rane, "Roles and Challenges of ChatGPT and Similar Generative Artificial Intelligence for Achieving the Sustainable Development Goals (SDGs)," *SSRN Journal*, 2023, doi: 10.2139/ssrn.4603244.
10. T. Haidegger *et al.*, "Robotics: Enabler and inhibitor of the Sustainable Development Goals," *Sustainable Production and Consumption*, vol. 43, pp. 422–434, Dec. 2023, doi: 10.1016/j.spc.2023.11.011.
11. G. Retsin, "Discrete Timber Assembly," Apr. 2020.
12. N. M. Larsen and A. K. Aagaard, "Exploring Natural Wood," presented at the ACADIA 2019: Ubiquity and Autonomy, Austin (Texas), USA, 2019, pp. 500–509. doi: 10.52842/conf.acadia.2019.500.
13. M. Tamke, M. Thomsen, and J. Riiber, "Complex Geometries in Wood," Jan. 2008, pp. 65–68.
14. S. Leder, R. Weber, D. Wood, O. Bucklin, and A. Menges, "Distributed Robotic Timber Construction," presented at the ACADIA 2019: Ubiquity and Autonomy, Austin (Texas), USA, 2019, pp. 510–519. doi: 10.52842/conf.acadia.2019.510.
15. K. H. Petersen, N. Napp, R. Stuart-Smith, D. Rus, and M. Kovac, "A review of collective robotic construction," *Sci. Robot.*, vol. 4, no. 28, p. eaau8479, Mar. 2019, doi: 10.1126/scirobotics.aau8479.
16. H. J. Wagner, M. Alvarez, O. Kyjanek, Z. Bhiri, M. Buck, and A. Menges, "Flexible and transportable robotic timber construction platform – TIM," *Automation in Construction*, vol. 120, p. 103400, Dec. 2020, doi: 10.1016/j.autcon.2020.103400.

 doi:10.20944/preprints202509.0123.v1



17. H. Bier, S. Khademi, C. van Engelenburg, J. M. Prendergast, and L. Peternel, "Computer Vision and Human–Robot Collaboration Supported Design-to-Robotic-Assembly," *Construction Robotics*, vol. 6, no. 3, pp. 251–257, Dec. 2022, doi: 10.1007/s41693-022-00084-1.
18. H. Bier, A. Hidding, C. van Engelenburg, and T. Ali, "Advancing Sustainable Approaches in Architecture by Means of Design-to-Robotic-Production," *SPOOL*, vol. 11, no. 1, pp. 65–70, July 2024.
19. C. Kasperzyk, M.-K. Kim, and I. Brilakis, "Automated re-prefabrication system for buildings using robotics," *Automation in Construction*, vol. 83, pp. 184–195, Nov. 2017, doi: 10.1016/j.autcon.2017.08.002.
20. K. Orlowski, "Assessment of Manufacturing Processes for Automated Timber-Based Panelised Prefabrication," *Buildings*, vol. 9, no. 5, p. 125, May 2019, doi: 10.3390/buildings9050125.
21. E. Vercruysse, "THE ANATOMY OF A SKELETON:: HYBRID PROCESSES FOR LARGE-SCALE ROBOTIC FABRICATION," 2020, pp. 226–233. doi: 10.2307/j.ctv13xpsvw.34.
22. P. F. Rocha, N. O. Ferreira, F. Pimenta, and N. B. Pereira, "Impacts of Prefabrication in the Building Construction Industry," *Encyclopedia*, vol. 3, no. 1, pp. 28–45, Dec. 2022, doi: 10.3390/encyclopedia3010003.
23. D. Popovic, "Off-site manufacturing systems development in timber house building: Towards mass customization-oriented manufacturing," PhD Thesis, 2018.
24. F.-C. Cheng, C.-C. Yen, and T.-S. Jeng, "Object Recognition and User Interface Design for Vision-based Autonomous Robotic Grasping Point Determination," presented at the CAADRIA 2021: Projections, Hong Kong, 2021, pp. 633–642. doi: 10.52842/conf.caadria.2021.1.633.
25. H. Chai, H. J. Wagner, Z. Guo, Y. Qi, A. Menges, and P. F. Yuan, "Computational design and on-site mobile robotic construction of an adaptive reinforcement beam network for cross-laminated timber slab panels," *Automation in Construction*, vol. 142, p. 104536, Oct. 2022, doi: 10.1016/j.autcon.2022.104536.
26. C. Chan, A. Pelosi, and A. Brown, "VR Controlled Remote Robotic Teleoperation for Construction Applications," presented at the eCAADe 2023: Digital Design Reconsidered, Graz, Austria, 2023, pp. 369–376. doi: 10.52842/conf.ecaade.2023.1.369.
27. J.-S. Hsu, Y.-T. Shen, and F.-C. Cheng, "The Development of the Intuitive Teaching-Based Design Method for Robot-Assisted Fabrication Applied to Bricklaying Design and Construction," in *HCI International 2022 Posters*, vol. 1583, C. Stephanidis, M. Antona, and S. Ntoa, Eds., in Communications in Computer and Information Science, vol. 1583. , Cham: Springer International Publishing, 2022, pp. 51–57. doi: 10.1007/978-3-031-06394-7_8.
28. M. Gharbia, A. Chang-Richards, Y. Lu, R. Y. Zhong, and H. Li, "Robotic technologies for on-site building construction: A systematic review," *Journal of Building Engineering*, vol. 32, p. 101584, Nov. 2020, doi: 10.1016/j.jobe.2020.101584.
29. M. Z. Naser, "Fire resistance evaluation through artificial intelligence - A case for timber structures," *Fire Safety Journal*, vol. 105, pp. 1–18, Apr. 2019, doi: 10.1016/j.firesaf.2019.02.002.
30. A. Rezaei Rad, H. Burton, N. Rogeau, P. Vestartas, and Y. Weinand, "A framework to automate the design of digitally-fabricated timber plate structures," *Computers & Structures*, vol. 244, p. 106456, Feb. 2021, doi: 10.1016/j.compstruc.2020.106456.
31. N. Rogeau, P. Latteur, and Y. Weinand, "An integrated design tool for timber plate structures to generate joints geometry, fabrication toolpath, and robot trajectories," *Automation in Construction*, vol. 130, p. 103875, Oct. 2021, doi: 10.1016/j.autcon.2021.103875.
32. S. Eduardo, "Minimizing Wood Waste by Respecting Its Natural Form Through AI," ArchDaily. Accessed: May 30, 2025. [Online]. Available: https://www.archdaily.com/1006700/minimizing-wood-waste-by-respecting-its-natural-form-through-ai
33. Z. Lai, Y. Xiao, Z. Chen, H. Li, and L. Huang, "Preserving Woodcraft in the Digital Age: A Meta-Model-Based Robotic Approach for Sustainable Timber Construction," *Buildings*, vol. 14, no. 9, p. 2900, Sept. 2024, doi: 10.3390/buildings14092900.
34. C. Klemmt, I. Pantic, A. Gheorghe, and A. Sebestyen, "Discrete vs. Discretized Growth," presented at the ACADIA 2019: Ubiquity and Autonomy, Austin (Texas), USA, 2019, pp. 542–553. doi: 10.52842/conf.acadia.2019.542.

35. A. de Paula, "Discrete Automation: Robotic Construction Workflow for Reconfigurable Timber Housing," 2023, Accessed: May 30, 2025. [Online]. Available: https://repository.tudelft.nl/record/uuid:c3436d86-c7d7-48c2-833a-d2fad07fabe5
36. F. Gramazio *et al.*, Eds., *The robotic touch: how robots change architecture ; Gramazio & Kohler Research ETH Zurich 2005-2013*. Zürich: Park Books, 2014.
37. A. Menges, B. Sheil, R. Glynn, and M. Skavara, *Fabricate 2017*. UCL Press, 2017. doi: 10.2307/j.ctt1n7qkg7.
38. A. Apolinarska, M. Kuhn, F. Gramazio, and M. Kohler, "Performance-Driven Design of a Reciprocal Frame Canopy - Timber structure of the FutureTree," Jan. 2021, pp. 497–504. doi: 10.52842/conf.ecaade.2021.1.497.
39. C. Robeller, "Integral Mechanical Attachment for Timber Folded Plate Structures," Lausanne, EPFL, 2015. doi: 10.5075/EPFL-THESIS-6564.
40. Y.-T. Shen and W.-T. Hsiao, "Robot Construction: The Development of Metal Bending Robotic Arm Based on Discrete Design Apply to Self-Standing Wall Construction," *Journal of Architecture*, vol. 122, no. 122, pp. 73–88, Dec. 2022, doi: 10.53106/101632122022120122004.
41. M. Claypool, M. Jimenez Garcia, G. Retsin, C. Jaschke, and K. Saey, "Discrete Automation," presented at the ACADIA 2020: Distributed Proximities, Online and Global, 2020, pp. 638–647. doi: 10.52842/conf.acadia.2020.1.638.
42. G. Restin, "Discrete Timber Architecture by Gilles Retsin," Issuu. Accessed: May 30, 2025. [Online]. Available: https://issuu.com/bartlettarchucl/docs/design-research-retsin-timber-04
43. P. Van Loon, D. Diener, and S. Harris, "Circular products and business models and environmental impact reductions: Current knowledge and knowledge gaps," *Journal of Cleaner Production*, vol. 288, p. 125627, Mar. 2021, doi: 10.1016/j.jclepro.2020.125627.
44. L. Van Gulck and M. Steeman, "The environmental impact of circular building design: A simplified approach to evaluate remountable building elements in life cycle assessment," *Building and Environment*, vol. 254, p. 111418, Apr. 2024, doi: 10.1016/j.buildenv.2024.111418.
45. D. Reisach, S. Schütz, J. Willman, and S. Schneider, "Digital Fabrication for Circular Timber Construction: A Case Study," *CE*, vol. 1, no. 2, Apr. 2024, doi: 10.55845/VWGD7873.
46. E. P. G. Bruun, E. Besler, S. Adriaenssens, and S. Parascho, "Scaffold-free cooperative robotic disassembly and reuse of a timber structure in the ZeroWaste project," *Construction Robotics*, vol. 8, no. 2, p. 20, Aug. 2024, doi: 10.1007/s41693-024-00137-7.