AUTOMATING CIRCULARITY IN TIMBER CONSTRUCTION THROUGH COLLABORATIVE CYBER-PHYSICAL RECONFIGURATION

Anja Kunic
Roberto Naboni

As the construction sector moves toward circularity, reconfigurable timber systems are gaining prominence for their potential to enable material reuse, adaptability, and extended carbon storage. This article introduces *ReconWood*—a cyber-physical construction framework that integrates computational design, robotic fabrication, human–robot collaboration, and mixed reality to operationalise circularity in timber architecture. By treating timber reconfiguration as an additive, iterative process, ReconWood supports the precise assembly and disassembly of modular components designed for reuse. The system incorporates voxel-based generative design, digital twins, and material passports to maintain continuity between physical elements and their lifecycle data, ensuring traceability and reuse across multiple construction cycles. Robotic mass production and mass customisation enable scalable fabrication, while collaborative assembly processes—augmented by real-time sensing and extended reality—facilitate adaptive decision-making and on-site flexibility. By embedding intelligence across digital and physical domains, ReconWood positions automation not as a marginal enhancement but as the foundational infrastructure for implementing circular construction at scale.

INTRODUCTION

In contemporary architecture, the resurgence of wood is not merely aesthetic or nostalgic but is fundamentally driven by its structural efficiency, regenerative properties, and capacity for carbon sequestration. While forests serve as Earth's largest terrestrial carbon sinks, timber buildings offer a unique opportunity to extend this function beyond the lifespan of trees. When timber structures are designed for longevity, adaptability, and reuse, the built environment can be reimagined as a globally distributed, dynamic system of long-term carbon storage that evolves in response to changing conditions. Material circulation is essential to realise this vision.

This research advances the thesis that automation is not a peripheral enhancement but a foundational enabler of circularity. It does so by embedding data continuity, operational reversibility, and adaptive decision-making across the entire material lifecycle.

To achieve this, the concept of material circulation must be expanded beyond physical flows. It is essential to establish robust data flows accompanying materials, encompassing information such as composition, origin, mechanical properties, design specifications, and lifecycle history. These data must remain continuously accessible to enable effective reuse. In this context, automating the planning and coordination of construction processes while maintaining real-time awareness of material conditions and flows becomes critically important. Automation enhances the scalability of circular construction by providing tools that bridge tacit, locally embedded material knowledge with the global information infrastructures through which the industry increasingly operates.

The vision of automating circularity promotes systemic change across scales. It involves reducing fragmentation within construction value chains through integrated digital workflows, improving interoperability among stakeholders through open-access tools and shared data environments, and enhancing transparency through real-time data acquisition and exchange. At its core, this approach fosters a cultural shift in which buildings are conceived to balance planetary health with temporary social, political, and economic requirements.

Contemporary digital and automation technologies make it possible to design buildings as documented and disassemblable material banks, from which materials may be recovered and reused after each lifecycle [1,2]. Robotic fabrication and assembly provide precise, repeatable, and efficient manufacturing processes, reducing construction waste and preserving the structural integrity of timber elements [3]. Additionally, the integration of Industry 4.0 (I4.0) technologies—including the Internet of Things (IoT), extended realities (XR), and human-robot collaboration—enhances the adaptability of construction processes under variable site conditions and unstructured environments [4–7]. In such contexts, data-driven control of fabrication and construction activities supports future disassembly and reuse. Likewise, data-informed design and engineering embed circularity at the inception of the construction process.

The use of digital twins further enables continuous tracking of a building's lifecycle, supporting structural adaptation and optimising reuse scenarios. AI-based design platforms can evaluate and propose structural configurations based on existing material inventories, facilitating a shift from new material production to intelligent, availability-driven reuse [8,9]. Material passports (MPs), underpinned by blockchain, IoT sensing, and digital tagging, support traceability and lifecycle management by maintaining a transparent record of each component's provenance, treatment, and mechanical properties [10–12]. These systems ensure that even as components are disassembled and reassigned, their value and usability are preserved.

Recognising information as the integrative element between digital tools and physical processes, SDU CREATE's research explores how generative, stress-informed design, collaborative human-robot construction, mixed reality (MR), and cyber-physical systems can together advance circular timber architecture [13–16]. In this context, we define automating circularity as a systemic framework for operationalising reuse, adaptability, and lifecycle management within the built environment. Crucially, this approach is not limited to improving efficiency; it enables circularity to function as a scalable and actionable paradigm. Without automation, circular construction remains confined to artisanal or small-scale experimentation, hindered by data discontinuities and the unpredictability of manual processes. Automation, therefore, is not a secondary enhancement but the operational foundation and infrastructural logic that renders circularity technically viable and strategically applicable across spatial, temporal, and structural contexts.

RECONWOOD: AUTOMATING CIRCULARITY THROUGH DATA-DRIVEN RECONFIGURABLE CONSTRUCTION

The ReconWood research framework advances the proposition that technologies typically associated with automation—robotic assembly, computational design, digital sensing, and real-time data integration—must be reinterpreted as enablers of circular logic. It introduces the reconfigurable design and construction of modular timber frame systems composed of digitally traceable elements as a scalable solution for a dynamic built environment capable of transformation, adaptation, and sustained carbon sequestration across multiple lifecycles. The framework involves closed-loop communication between computational design environment, materials and collaborative human-robot construction processes with real-time data acquisition to ensure the traceability, reversibility, and reusability of building components.

The system is conceived through data-driven generative design supporting the optimisation of spatial and structural performance while anticipating future disassembly. Robotic fabrication technologies are used to produce and assemble the timber elements into reconfigurable frames ensuring precision and consistency while reducing damage during installation and enabling clean deconstruction. In contrast to the conventional construction where material histories are fragmented, component conditions remain undocumented, and disassembly often results in loss or damage, the ReconWood construction parts integrate embedded material identifiers and digital twins maintaining continuity between physical components and their lifecycle data, and ensuring that each element's history, condition, and reuse potential remain accessible. Together, these technologies form a cyber-physical infrastructure through which materials can circulate within and across building projects, rendering circularity a designable and executable process rather than a conceptual aspiration.

In this sense, the ReconWood concept builds upon and extends the historic paradigms of reconfigurable "programmed architecture" and cybernetics [17-19] to pursue adaptable, resource-efficient, and user-responsive architectural environment. The system of stress-informed timber structures, optimised for robotic assembly and disassembly, has evolved through a series of research prototypes (Fig. 1). These are composed of layered assemblies of modular construction parts connected through semi-interlocking, cross-shaped shear keys secured with reversible steel fasteners. Each part is individually identified via QR code imprints, which link the physical element to its digital twin, allowing for uninterrupted tracking and tracing across uses.

The multi-resolution timber frames reveal the underlying computational voxel-based design methods, used to translate structural conditions and material constraints into modular tectonic rules. This approach enables rapid iteration of designs that satisfy both performance criteria and reusability demands. By embedding digital intelligence within modular timber structures, ReconWood reconceives the building not as a fixed form but as a dynamic and evolving system.

Reversible timber tectonics and construction kit of parts

The reversible ReconWood construction system is based on a kit of parts arranged in layered orthogonal frames with varying material densities. The kit of parts (Fig.2), produced out of laminated veneer lumber (LVL), is available in three cross-sectional heights and a range of modular lengths, allowing for scalability and customisation in different architectural applications. The basic modular unit is represented by a single cross-shaped shear key. The shear keys are designed to enhance the shear capacity of the bolted joints and facilitate assembly and disassembly by a single robot arm [20,21]. During assembly, the male and female sides of the joints interlock, preventing displacement and rotations of the parts and ensuring precise positioning.

LVL was chosen as a material due to its high strength, dimensional stability, and resilience to environmental fluctuations. These properties ensure that modular parts maintain their precision and integrity over multiple reconfigurations. Furthermore, by replacing commonly used wood screws and nails with pre-drilled bolt-nut fasteners, localised material damages are prevented and the ease of disassembly is ensured. Such features enhance the durability of each element, supporting an extended lifecycle within a circular construction framework.

Additionally, the integrated QR codes enable seamless material tracking and data-informed construction planning. The QR codes link the physical parts to cloud-hosted databases that are accessible to different tools, processes, and stakeholders, fostering an adaptive material ecosystem.

The construction kit is fabricated and prepared for its final use through a two-stage procedure (Fig.3). The first one involves the robotic *mass production* of generic reconfigurable parts through subtractive manufacturing of shear keys. These parts can be virtually infinitely reused and continuously reconfigured with no additional processing or interventions. This process currently relies on single-robot work. However, it can be industrially scaled and parallelised using multi-spindle setups, enabling the rapid production of large numbers of shear keys within minutes. Featuring high-speed production, high precision and repeatability, this process is fundamental for achieving a consistent assembly process and low tolerances among numerous construction parts. In this stage, a substantial stock of pre-fabricated beams is generated and made available for further customisation in response to the specific design goals.

On the other hand, some construction parts require additional fabrication of design-specific features and are subject to the robotic *mass customisation* process. This mostly includes the generation of additional lateral holes on the parts of the higher cross-section to accommodate specific joining needs. The combination of these two processes leverages the benefits of tailored design, offering flexibility and adaptation alongside the efficiencies and sustainability of standardisation and mass production.

Automating Design: Stress-driven generative design of multi-resolution timber framing

ReconWood leverages voxel-based generative design to define multi-resolution structural timber frames optimised for both load distribution and material reuse. The voxel-based workflow is driven by a scalar field containing performance criteria such as structural stability, spatial functionality, and environmental conditions. In response to this field, an iterative computational massing process is performed, selectively removing or preserving material (voxels) while ensuring structural stability. This rapid volumetric shaping enables high flexibility in spatial exploration during early design stages. Once a design option is selected, the resulting voxelised grid is translated into a light-frame structure with varying densities based on spatial and structural parameters. In particular, voxel attributes such as orientation, neighbour dependencies and internal stresses are analysed to determine construction rules. This translation process converts abstract voxelised forms into materialised modular units, the *maxels*, with specific tectonic properties (Fig.4). The distribution of varying maxel resolutions is iteratively adjusted based on feedback from Finite Element Model (FEM) and satisfying design solutions are achieved through a multi-criteria optimisation process, aiming to reduce the amount of employed material while satisfying load-bearing requirements. This allows for efficient material allocation and an adaptive framing strategy that responds dynamically to design constraints.

The voxel-maxel methodology governs the organisation of modular timber parts in two types of structures, *horizontal* and *vertical* (Fig.5), with their corresponding construction rules. The horizontal ReconWood slabs [22]

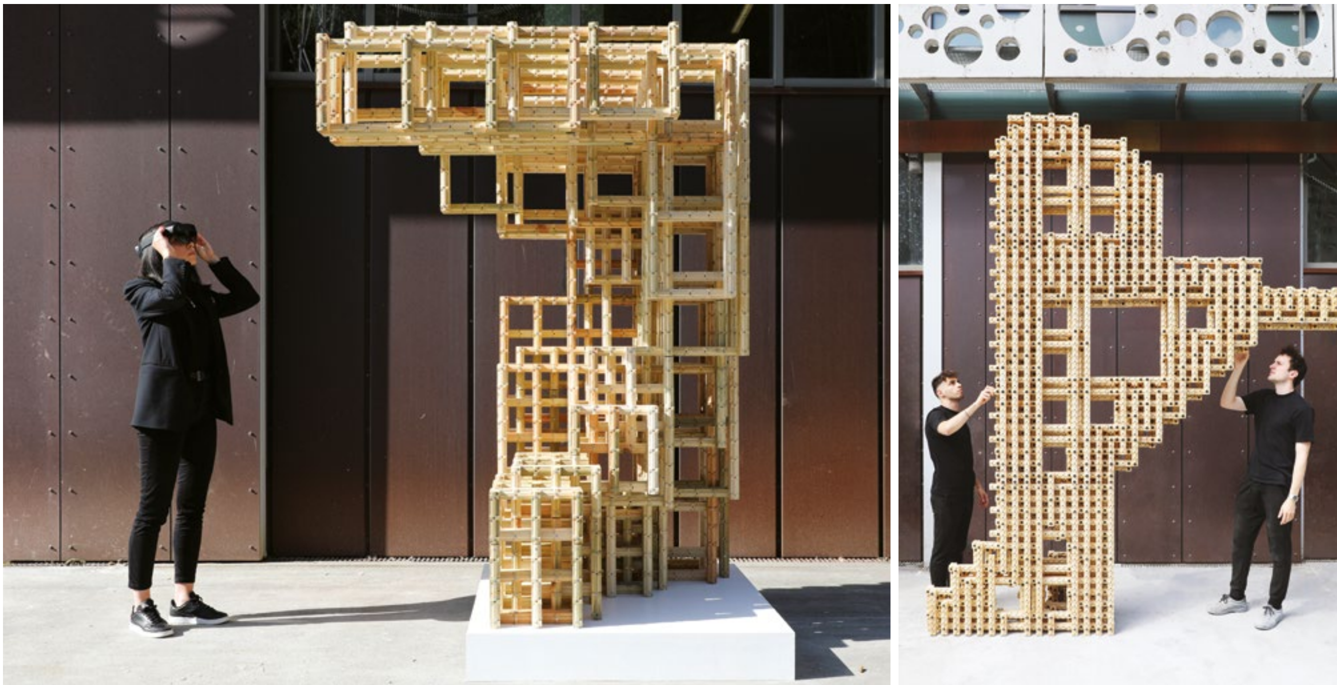

Figure 1: Incremental ReconWood construction prototypes:
a) ReconProto 01, b) ReconProto 02, c) ReconWood wall.

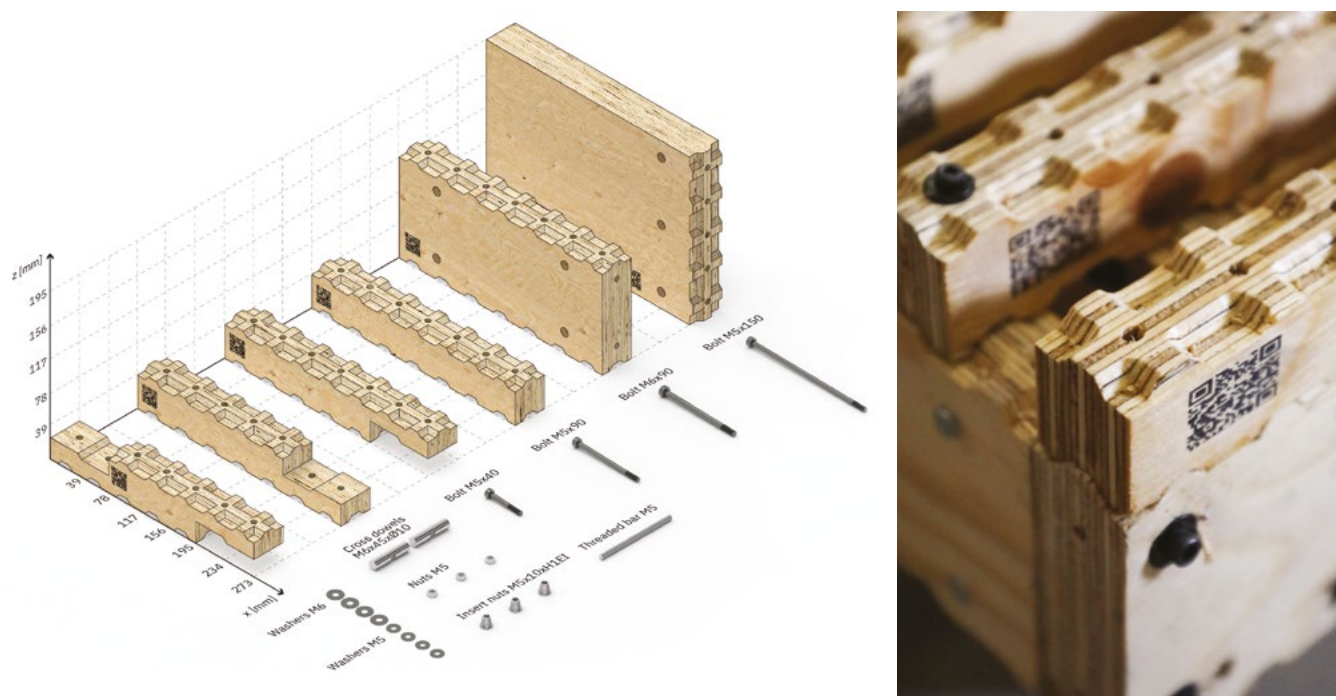

Figure 2: a) ReconWood modular construction kit; b) A close-up view of the construction parts with QR codes.

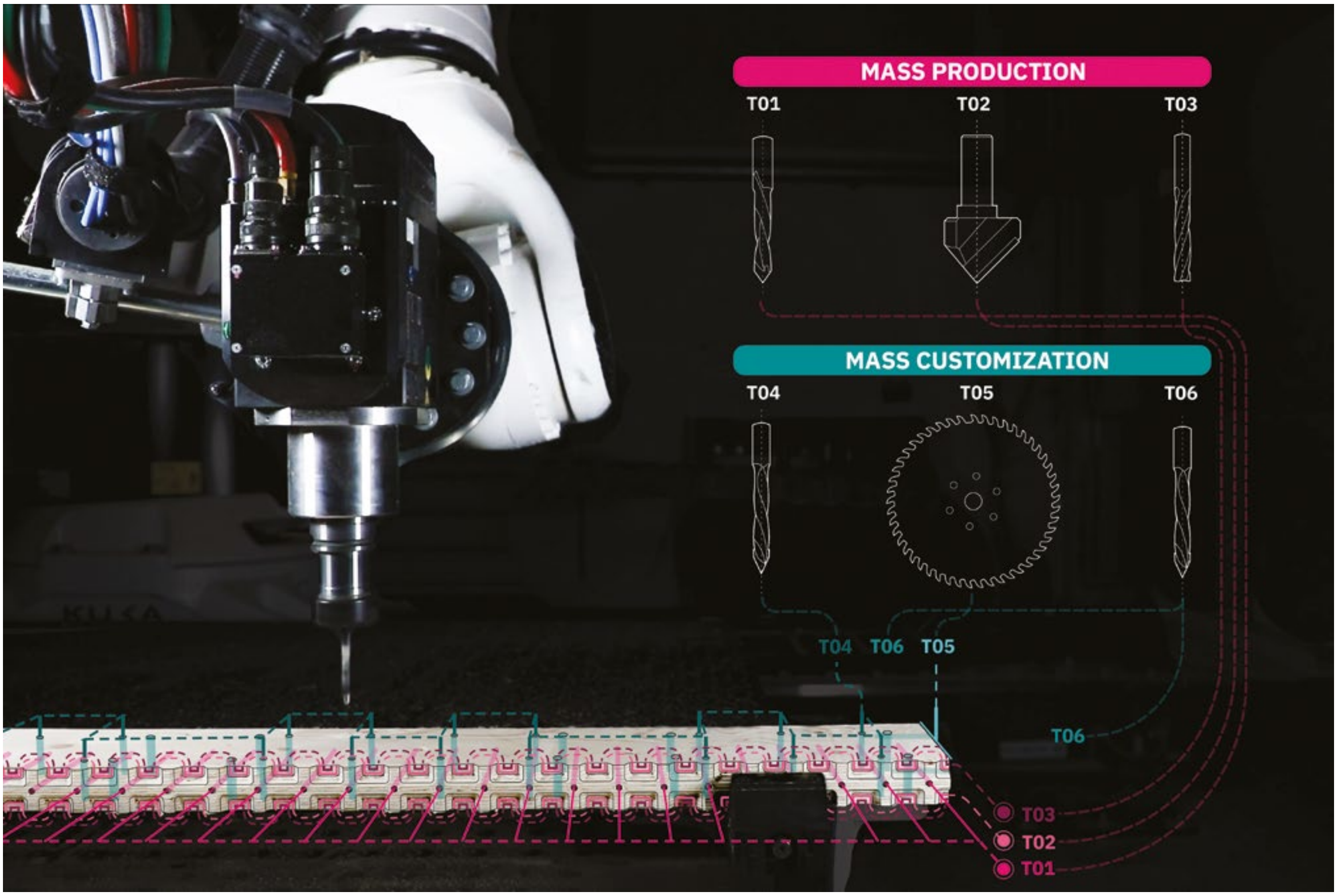

Figure 3: A two-step robotic fabrication of the construction parts.

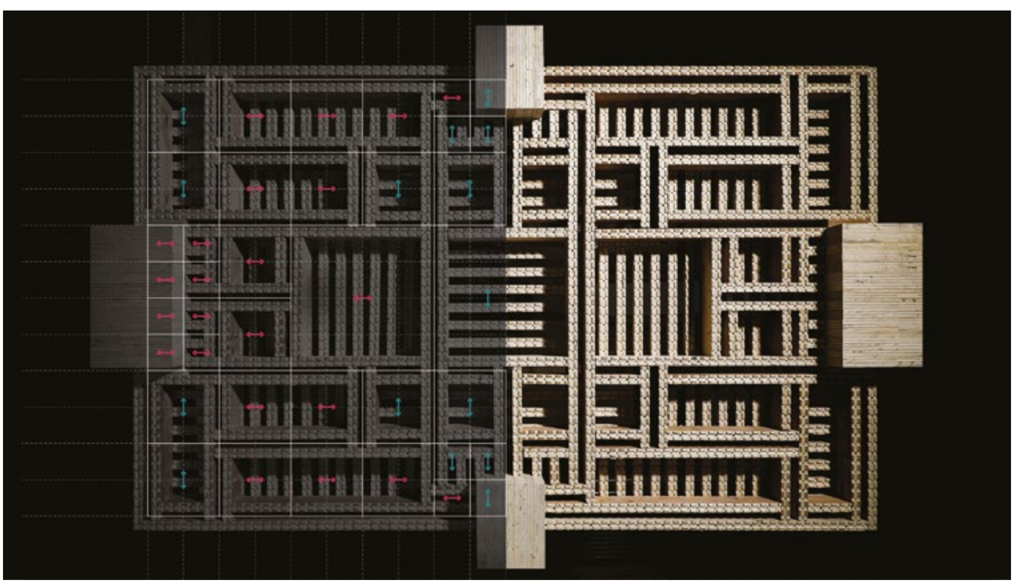
Figure 4: A bottom view of the ReconWood Slab structure highlighting the stress-driven computational design process used to generate it.

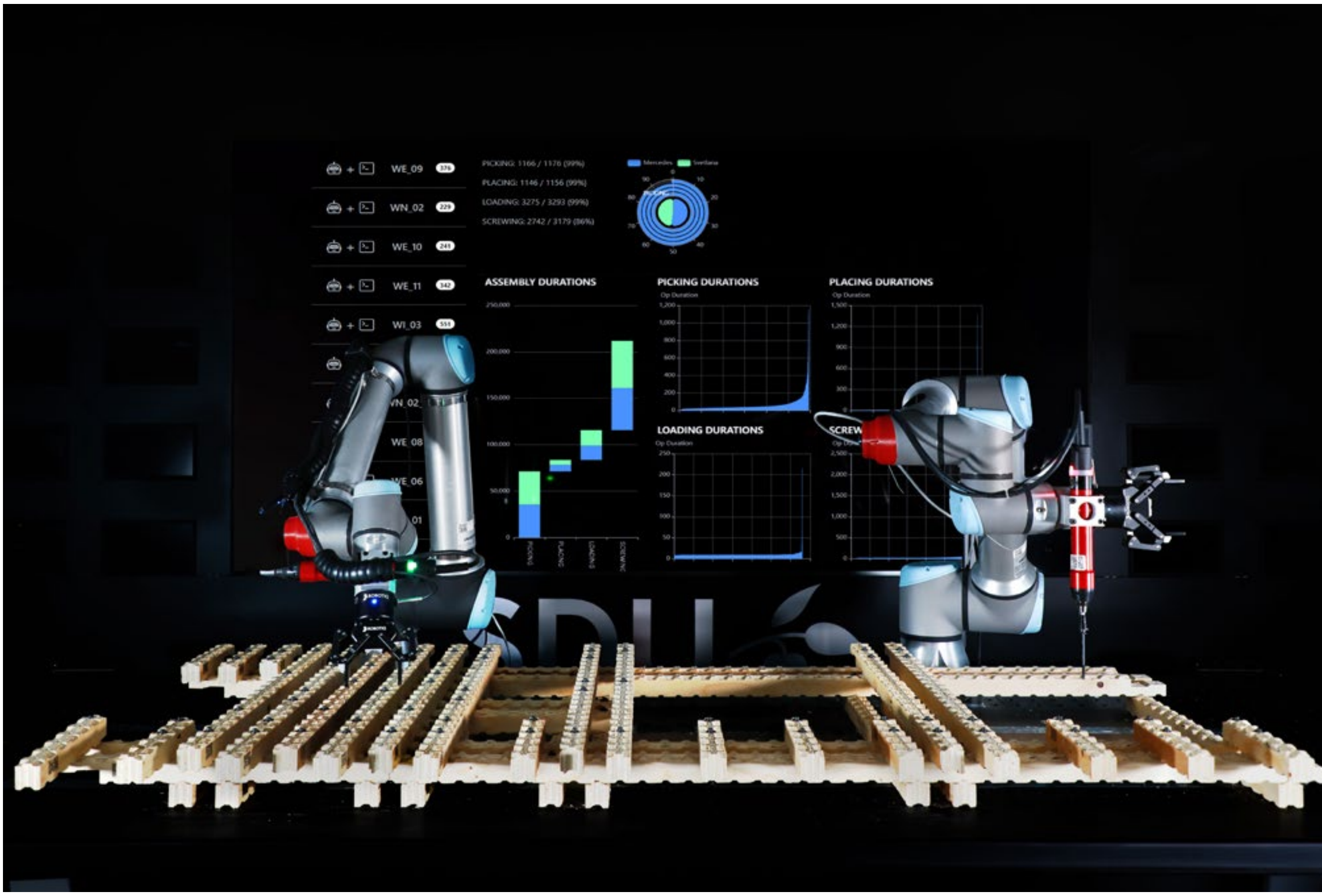

Figure 5: Cyber-physical collaborative robotic assembly of ReconWood structures.

Figure 6: Cyber-physical collaborative assembly of ReconWood structures aided by Mixed Reality.

consist of a double-layer system, including primary and secondary beams. The primary beams follow discretised Principal stresses in their orientation and density. They are characterised by higher cross-sections and in-plane connections in the form of double-bolted butt joints to increase bending moment capacity. The secondary beams with lower cross-sections are bolted on top of the primary beams, serving as additional structural stiffeners. The vertical structures, on the other hand, are characterised by a multi-layer system of parts with the same cross-sections, interconnected perpendicularly at different layers to form closed frames of various densities. The technological features of the system reflect the underlying computational principles through which they were conceived, driven by the functional and structural requirements they should serve. The data-driven material allocation and control herein introduced allow for an informed reconfigurability and reuse in future material life cycles.

Automating Assembly: Collaborative cyber-physical assembly as an enabler of material reuse

The assembly of ReconWood structures is carried out layer by layer, distributing the modular parts into controlled material layouts. This process resembles the production of functionally graded structures with additive manufacturing while preserving the reversibility and economy of mass-produced parts. It is based on the collaborative efforts of two UR10e robots, handling placement and fastening tasks with real-time sensing (Fig.6), and human operators wearing MR headsets, overseeing and intervening in the process when necessary (Fig.7). Additionally, the integration of MR allows humans to track materials and interact with their digital twins in real time, accessing design specifications, structural data, and historical usage records. Such sociotechnical collaboration, where humans and robots “see” and interact with the same datasets in a shared physical space, enhances flexibility in decision-making and error mitigation during the assembly and improves construction's adaptability to varying unknown conditions while preserving precision, efficiency, and information integrity.

Digital and physical processes, tools and operating agents communicate via closed-loop cyber-physical dataflows to ensure continuous material data acquisition, processing and exchange. The acquired assembly data is highlighted on the ReconWood website, providing insights into the most relevant performance indications. This digital-material integration establishes a scalable framework for circular construction, where materials are continuously repurposed without loss of structural integrity, reinforcing a sustainable and intelligent approach to timber architecture.

CONCLUSION: TOWARD CIRCULAR AUTOMATION IN TIMBER CONSTRUCTION

The architectural vision of ReconWood shifts the paradigm of material use, extending the lifespan of timber components beyond a single building cycle and establishing a regenerative framework. The research introduces reconfigurability, combined with digital material tracking and adaptive assembly strategies, as a way to reduce material waste, extend carbon storage and achieve architectural flexibility, preventing the need for building demolition.

The potential of automation in circular timber construction lies in its capacity to create a continuous feedback loop between design, fabrication, and assembly, allowing timber elements to be strategically allocated, reconfigured, and repurposed with minimal intervention. This approach fosters a new material economy where digital intelligence embedded in construction components enables informed reuse decisions, ensuring that each timber element retains its value across multiple life cycles.

Beyond its technical implications, the system presents a broader vision for the future of architecture—one in which buildings are no longer static entities but dynamic, reconfigurable systems capable of evolving in response to changing needs. The convergence of automated material tracking, robotic assembly, and human-machine collaboration facilitates an adaptive built environment, where architecture is conceived as an ongoing process rather than a finite product. The interplay of physical and digital data streams within the cyber-physical construction framework ensures that every assembly, disassembly, and transformation contributes to a long-term circular strategy, redefining the relationship between design and material sustainability.

For automated circular timber construction to be widely adopted, several challenges must be addressed. Standardisation of reconfigurable timber components and their corresponding digital tracking systems will be crucial in ensuring interoperability across different projects and scales. The integration of AI-driven predictive analytics could further refine material lifecycle management, enabling structures to anticipate and adapt to environmental and load conditions autonomously. Additionally, advancements in policy frameworks and industry regulations will play a pivotal role in fostering the transition towards a construction economy where materials are not simply consumed but continuously repurposed within a closed-loop system.

By positioning timber construction within the logic of cyber-physical automation, ReconWood advances the discourse on sustainability beyond mere resource conservation, advocating for an architecture that is intelligent, responsive, and inherently circular. The potential to scale such methods to larger architectural typologies, from housing to infrastructure, suggests that automation will be instrumental in shaping a future where timber buildings function as dynamic material reservoirs rather than as endpoints of a linear construction process, fundamentally redefining how the built environment is conceived, constructed, and perpetually renewed.

ACKNOWLEDGEMENTS

The ReconWood research has been developed by SDU CREATE - University of Southern Denmark and supported by SDU I4.0 Lab as infrastructure partner and Stora Enso as material partner. Furthermore, the authors are grateful for the significant scientific and technical contributions of internal and visiting researchers as well as internal and international students who took part in the development of different prototypes: ReconWood Proto 01 and ReconWood Proto 02: Roberto Cognoli and Angelina Garipova.

ReconWood Slabs and ReconWood Walls: Giuseppe Marrone, Davide Angeletti, Ardeshir Talaei, Hamed Hajikarimian, Daniele Florenzano, Pedro Vindrola, and the student participants of CREATE's Summer School on Experimental Architecture X Robotic Timber Assembly (Thomas Bellavere, Silas Bolund Falkø, Rasmus Peter Mott Frandsen, Margherita Camilla Guffanti, Mai Linh Isaver, Thomas Buris Larsen, Hedegård Madsen, Frederik Mariager, Louise Chalee Nguyen, Kim Nikolajsen, Bjørg Kamp Ostrup, Sofie Yan Rasmussen, Sigrid Samsing, Juliane Seiffarth, Lukasz Smolej).

Figure 7: ReconWood architectural demonstrator showcasing the integration of wall and slab structures.

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