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RESEARCH

Multi-functional adaptive robotic fabrication strategy for irregular reclaimed timber in large-scale building components for circular construction

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Abstract

Reusing wood in construction is crucial for advancing circular practices as global demand for timber exceeds sustainable supply. This research investigates an adaptive robotic fabrication strategy for constructing structural architectural components from irregular reclaimed timber. Building on prior work in digital upcycling and augmented-reality-assisted assembly, this study develops a multi-functional fabrication framework that integrates automated pick-and-place, nailing, drilling, and doweling into a coherent robotic process for non-standard timber elements. Reclaimed timber from industrial offcuts, demolition, and used pallets is scanned and digitally mapped to capture geometric and material variability. Computational design tools then optimize the arrangement of these elements within structural assemblies, balancing performance and fabrication feasibility. Using a 6-axis industrial robot with a linear axis, this system executes adaptive pick-and-place operations and mono-material joining through pneumatic wood nailing, drilling, and doweling, avoiding metal connectors or adhesives. The integrated workflow combines open- and closed-loop control, laser sensing, and parametric design to manage tolerances in geometry and surface quality. Two full-scale case studies, consisting of frame and floor slab components, demonstrate the system's feasibility and architectural application. The results position multi-functional robotic fabrication as a key enabler for circular construction, transforming reclaimed timber from low-grade waste into a high-value building resource. The research advances digital design, fabrication, and sustainability by framing robotic upcycling as a pathway toward resource-efficient architectural production.

Keywords Adaptive robotic fabrication · Reclaimed timber · Circular construction · Computational design · Timber-to-timber connections · Digital upcycling

1 Motivation

The architecture, engineering, and construction sector remains a significant driver of global environmental impact, accounting for nearly 50% of global resource extraction and between 37 and 39% of energy- and process-related CO2 emissions (Global Alliance for Buildings and Construction, International Energy Agency and the United Nations Environment Programme (2019): 2019 global status report for buildings and construction: Toward a zero-emission, efficient and resilient buildings and construction sector 2019; United Nations Environment Programme: 2023 Global Status Report for Buildings and Construction: Beyond foundations - Mainstreaming sustainable solutions to cut emissions from the buildings sector 2023). Moreover, projections indicate that global timber demand is set to almost triple between 2010 and 2050, resulting in an increasing wood supply gap that cannot be met solely by primary forests (Beck-O'Brien et al. 2022). Even as sustainable design practices advance, architectural production continues to rely on linear resource chains and standardized materials. Timber—though renewable—faces increasing constraints due to long forestry cycles, land-use pressures, climate impact, and sustainability imperatives for forestry practice. At the same time, the existing building stock and industrial production streams in Germany contain vast quantities of reusable wood elements that are typically discarded or incinerated (Steger

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et al. 2019). Reusing this reclaimed timber represents a significant opportunity to extend embodied carbon retention and extend material lifecycles, yet practical implementation is still hindered by geometric irregularity, embedded fasteners, and uncertain structural performance.

Recent developments in digital and robotic fabrication have opened new opportunities to address these challenges. By coupling sensing, computational modeling, and adaptive control, robotic systems can bridge the gap between the precision of digital design and the imprecision of reclaimed materials. Digital tools, such as 3D scanning, photogrammetry, and computational inventory management, allow the geometric characterization and digital classification of reclaimed timber, forming the foundation for reuse-based design workflows. Different approaches at the computational design level aim to generate designs from inventories (Zanetti et al. 2025). In continuation of that, this paper seeks to explore solutions for closing the loop from design to fabrication, as these designs cannot generally be fabricated using current standard fabrication approaches, which assume standardized timber with minimal tolerances.

At the same time, recent research explores how digital and robotic systems can integrate reused materials into construction. Demonstrators, such as the Re/Place Pavilion (Studio Chris Fox 2022), Nail-It Pavilion (Fischer et al. 2024), and TerraTimber project (Fischer et al. 2025), have shown how digital design concepts can be generated and fabricated using digital tools, such as CNC machines and augmented-reality-assisted processes, to position irregular timber elements. These hybrid workflows combine human skill with computational precision but still depend heavily on manual intervention or single-task machine setups. To advance toward scalable reuse, future fabrication systems would need to perform multiple operations and respond adaptively to diverse material conditions.

State-of-the-art robotic timber construction has achieved high precision and scalability through dedicated automation platforms (Cheng et al. 2025). Yet most current systems remain process-specific, optimized for standardized uniform stock and pre-calculated toolpaths. They lack the adaptability required to manage the irregular geometries of reclaimed timber. Recent investigations into tactile robotic assembly and hybrid intelligence for materialization emphasize the value of multi-sensor feedback (force, distance, or vision) to enable robots to perceive and adapt to material variation in real time (Çapunaman and Gürsoy 2024; Belousov et al. 2019; Cote et al. 2024). This represents an essential shift from static automation toward adaptive fabrication, in which robotic systems interpret and react to physical feedback rather than merely executing pre-defined trajectories.

In this context, the development of multi-functional robotic fabrication frameworks that integrate multiple feedback-driven and mechanically adaptive operations constitutes a key challenge. By merging multiple discrete operations within a single robotic end effector and control framework, such systems can achieve both process efficiency and adaptive response. Multi-functionality suggests reducing setup time, eliminating manual tool exchange, and enabling continuous fabrication sequences informed by sensor feedback. A robot can thus handle geometric irregularities, surface tolerances, and material variations as they happen during assembly.

The research presented in this paper builds directly upon these advances. It introduces a multi-functional adaptive robotic fabrication system that integrates picking, placing, nailing, drilling, and doweling within a single, sensor-driven workflow. Designed for timber, the system merges adaptive mechanical and sensor feedback. Beyond its technical contribution, this research situates itself within a broader discourse on digital craft and circular construction, emphasizing how robotic adaptability can enable resource-efficient, materially intelligent construction workflows. (Fig. 1) The project thus advances the notion that the future of architectural robotic fabrication lies not only in the automation of standardized processes, but in multi-functional, adaptive, and feedback-driven systems that actively mediate between computation, material, and fabrication.

2 Methods

This research presents the development of a multi-functional adaptive robotic fabrication system that integrates several discrete timber-fabrication operations into a continuous, sensor-driven workflow derived from a computational design model. The operations are picking, placing, nailing, drilling, and doweling. Two full-scale case studies of computationally designed building components are presented. First, a research study of structural frame components forming a modular, reusable exhibition structure. Second, the development of a hybrid reclaimed floor slab combining reclaimed timber and earth. Along the lines of those two case studies, the focus is on developing an adaptive robotic fabrication system. The objective is to demonstrate how a single robotic platform can fabricate large-scale structural building components while adapting the fabrication process to irregular, heterogeneous reclaimed timber elements. The inventory of reclaimed materials comprises industrial offcuts, discarded pallets, and demolition timber. Non-standard geometries, variable thicknesses, and surface imperfections characterize all those materials. The method is to aggregate these materials with wood-based connectors to ensure full recyclability of the resulting components and to eliminate the need for metal fasteners and adhesives, inspired by previous research (Ruan et al. 2021, 2022; Han et al. 2023). The system is therefore designed to accommodate geometric variation and

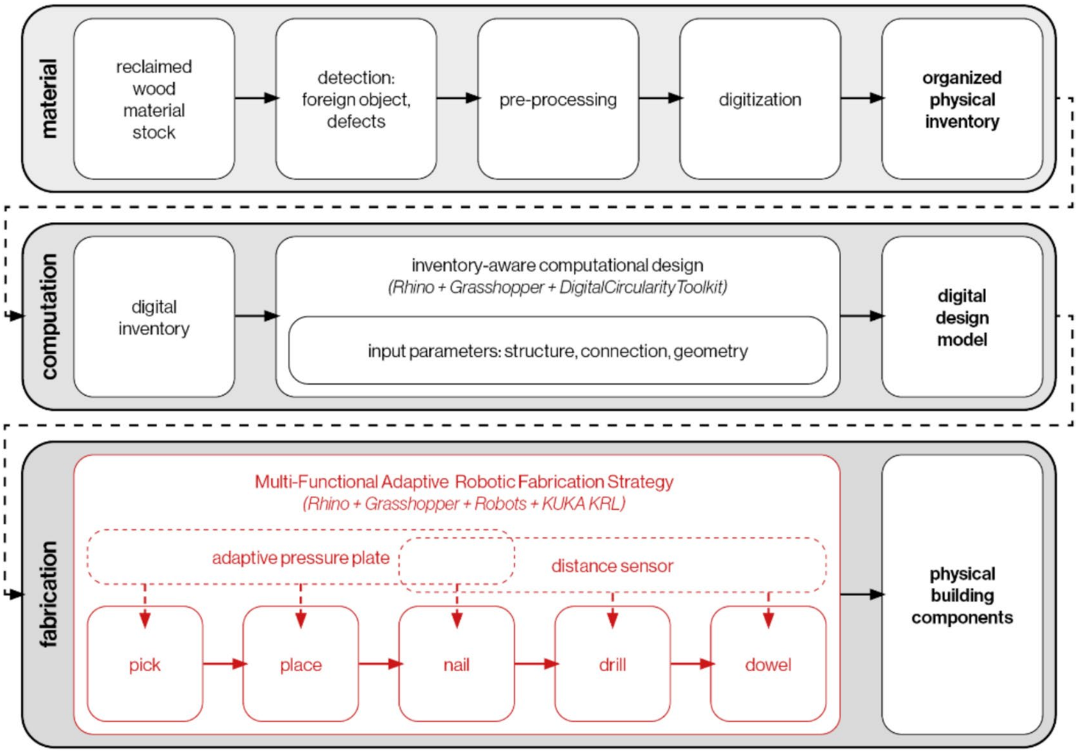

Fig. 1 Multi-functional adaptive robotic fabrication framework

inconsistent wood quality during robotic fabrication, and to support circular construction through a fully mono-material assembly.

2.1 End effector design for multi-functional adaptive fabrication

The robotic platform consists of a KUKA KR210 R3300-2 K F robot mounted on a KL 4000 linear axis. Its 250 kg payload capacity enables the integration of multiple active tools within multi-functional end-effectors. The first iteration of the setup, corresponding to the first case study, combines a vacuum gripper and a pneumatic nail gun for the adaptive fabrication of frame components. In this configuration, both tools are mounted opposite each other to provide the maximum workspace possible. For the picking-and-placing operation, a Schmalz FXP-SW60 vacuum gripper is mounted on four spring plungers, allowing an adaptive mechanical behavior, namely vertical compliance to compensate for surface tolerances and handle elements of varying thickness (Fig. 2a). For the nailing operation, a Lignoloc F60 CN15-PS90-H pneumatic nail gun with a custom-designed pressure plate stabilizes elements to prevent movement and absorb recoil (Fig. 2b). For the second case study, the fabrication of a floor slab component, the system is extended with a high-torque Hiteco QE-1F spindle equipped with a 12 mm drill bit, and a pneumatic hammering mechanism to introduce doweling. The spindle, the heaviest component, is positioned close to the flange to reduce inertial torque. At the same time, the remaining tools are arranged in a 135° cluster with three discrete 45° working orientations to minimize collision risk and increase reachability (Fig. 3). All three tools — vacuum gripper, nail gun, and palm nailer — are mounted on exchangeable equal base modules to provide flexibility for future iterations and tool upgrades.

2.2 Computational design

The reuse workflow is grounded in a sequence that begins with the creation of a digital inventory of reclaimed timber elements and concludes in their aggregation into larger structures (Fig. 4).

Each element is first digitized using image-processing methods that capture its two-dimensional outline and height, and is then labeled to link the physical piece to its corresponding digital record. These interconnected inventories form the basis for subsequent design and fabrication handoff. Computationally, the aim is to anchor the process in the material inventory, treating it as the starting point and principal constraint, while specifying as little geometry and topology as possible in advance. Regardless of the specific method, design viability depends on adherence to structural and connection requirements, such as minimum counts of nails or dowels per joint and minimum spacing

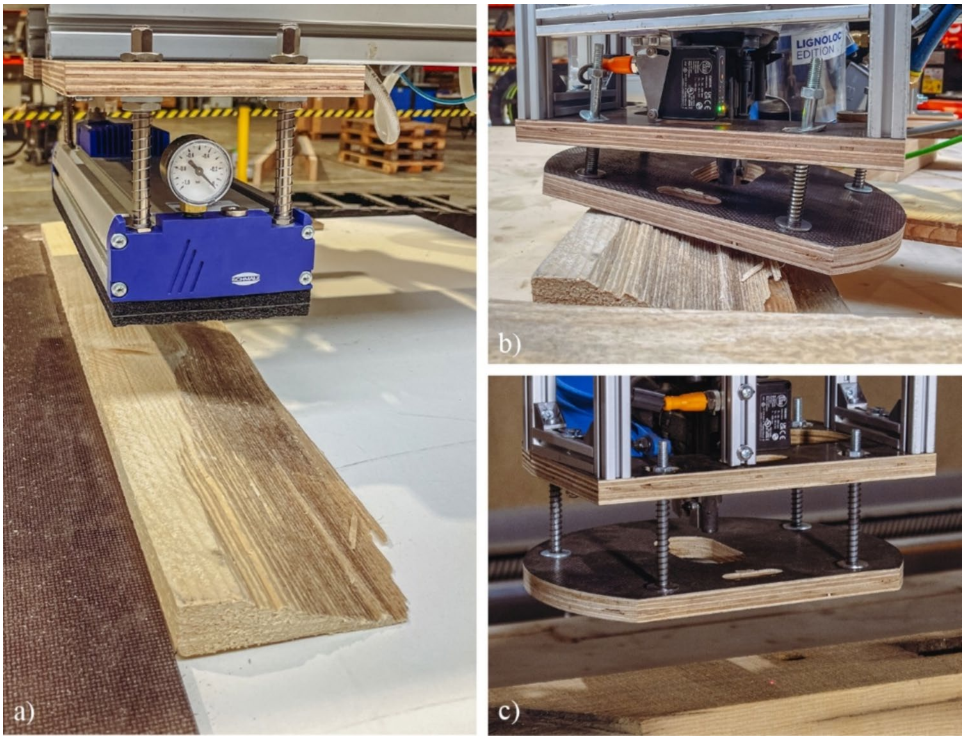

Fig. 2 Spring plungers (a, b, c), Adaptive pressure plate (b, c), Laser distance sensor (b, c)

and edge-distance constraints (minimum center-to-center distances along and across the grain, and minimum distances from fasteners to member edges and ends, specified to avoid splitting and ensure reliable load transfer). Optimization routines enhance either performance (e.g., inventory utilization) or resource efficiency (e.g., waste minimization) and may be combined as needed.

The first case study considers half-arched building components and adopts a top-down approach: a basic, parameterized truss topology is modified by a custom design script that generates multiple options by relocating nodes within the plane. Across all variants, the common design features are the boundaries and the half-arch triangulated interior web. Each option is checked against the inventory and evaluated for structural performance, minimum fastener counts and spacing, inventory utilization relative to fresh-timber supplementation, fabrication time, cutting operations, and resulting waste. Waste minimization is performed as a length-based stock-allocation step. For each generated design option, required member lengths are matched to available reclaimed elements, and the resulting offcut waste is computed as the unused remainder length per assignment. This minimum-total-waste matching is solved in the DigitalCircularityToolkit (DigitalCircularityToolkit 2026) using a minimum-cost assignment (Hungarian) algorithm, where the objective function is the summed remainder length, including a penalty for primary timber supplementation.

The second study considers floor slab components and employs a bottom-up approach adapted from bin-packing logics. In this case, an iterative algorithm is implemented, and geometry is defined only by boundary conditions, while element selection and placement are driven by the inventory and randomization. The main connections are made with 12 mm wooden dowels sized to structurally activate three layers simultaneously. Because the search is stochastic and locally greedy, the algorithm generates a large set of options, which are then evaluated against structural and performance criteria, with particular attention to timber-earth shear behavior.

Both approaches rely on layered assemblies. Because thickness uniformity cannot be assumed for a varied, often warped inventory, elements are grouped by similar thicknesses with a ± 2.5 mm tolerance; residual deviations are addressed during fabrication through local adaptation (Fig. 2). Once a design is selected, the script outputs fabrication-ready data as a 3D model encoding element positions, labels, and joining coordinates that form the base for robotic fabrication in the next step.

2.3 Control setup

The control logic for the fabrication system uses a hybrid approach, combining open-loop routines for predictable positioning with sensor-driven closed-loop correction to achieve adaptability. The primary adaptation mechanism addresses height uncertainty inherent to non-standard materials: a laser distance sensor performs a single measurement immediately before each operation, updating the

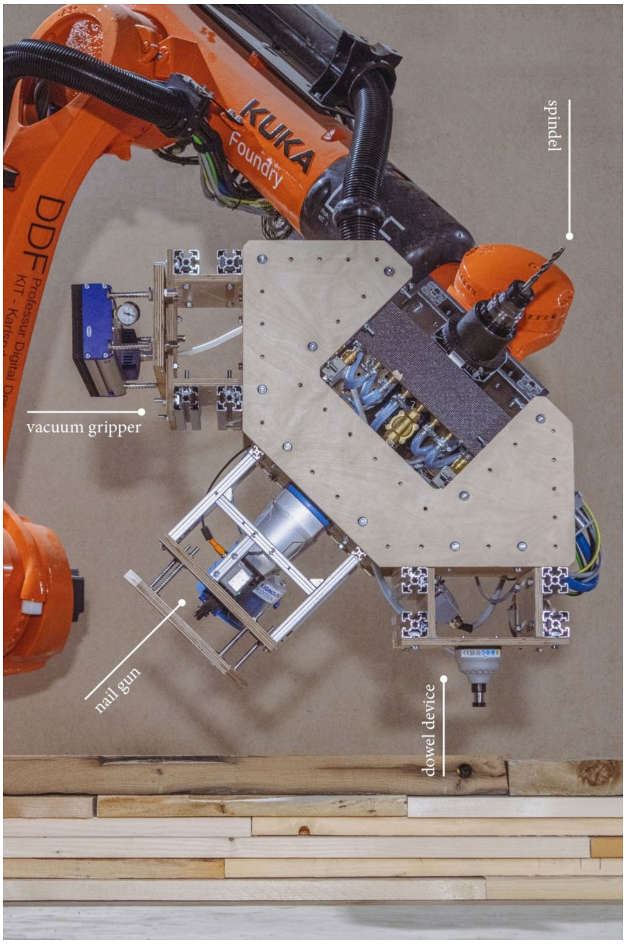

Fig. 3 Multi-functional robotic end effector, Second case-study

linear z-movement. This measured value dynamically computes and applies a Z-offset to compensate for material surface irregularities and dimensional instability.

The control program employs a hierarchical architecture: high-level orchestration, design-to-path translation, and overall sequencing are scripted in Grasshopper using the ROBOTs plugin. Low-level execution is delegated to KUKA Robot Language (KRL) on the controller. This hybrid configuration leverages the Grasshopper plugin Robots for complex geometric logic while reserving KRL for time-critical, controller-level functions, specifically reading the distance sensor and executing sensor-referenced closed-loop moves. Functionality is encapsulated in modular KRL subroutines, which bundle motion primitives and safety interlocks. This ensures consistent, maintainable code across all tasks. A concise user-supervision layer is maintained: the entire sequence is operable via the pendant, with embedded safety pauses allowing for visual checks and one-button override capability.

2.4 Case study one: frame component

At the beginning of each pick-and-place sequence, the element calculated next for operations by the fabrication script is manually placed on a defined picking template next to the fabrication table to enable orientation-precise picking. The end effector moves into position, waiting for human confirmation to start the routine. This step integrates one manual step into the workflow: identifying the required element from the inventory and confirming its position in the template. After activating the sequence, this system runs the picking routine, optimized for speed and safe handling of elements. First, the gripper is lowered to contact the elements' surface, while the distributed spring plungers compensate for tolerances (Fig. 2a). The element is then secured by applying a vacuum force to its surface. Moving up occurs at a lower speed to allow all plungers to fully extend before placing. Following this step, the sequence for placing is automatically started. The system first moves to a secure point above the fabrication table to avoid collisions, then to a corresponding point 20 cm above the final placement position while orienting the element. The following routine is activated, and the element is placed (Fig. 6a). After this operation, this system moves to a safe point to rotate the end effector by 180° for tool change. During nailing, a pneumatic nail gun is used to fix elements in precalculated positions to connect them structurally (Fig. 6b). An integrated distance sensor measures local height offsets before moving to the final nail position (Fig. 2c). After the distance is measured, the nail gun is moved into an executable position. At the same time, a pressure plate stabilizes the element during nailing, thereby maintaining geometric accuracy (Fig. 2b). These steps are repeated until a frame component is fabricated, following a layer-by-layer logic (Fig. 5).

2.5 Case study two: floor slab

Even though the computation model differs, the sequences for picking, placing, and nailing follow the same logic as for the frame components. The difference in this study is that wood dowels replace wood nails to improve the structural connection between elements. The use of wood nails is reduced to hold elements in position before the drilling routine starts. The four-stage closed-loop drilling sequence combines approach, height detection, drilling, and retraction to ensure drilling holes of consistent depth despite surface variations and height tolerances (Fig. 6c) ood residue to escape and avoid friction-caused burning. The doweling sequence utilizes a modified pneumatic mechanism based on a Stanley & Bostitch palm nailer. By introducing a custom 3D-printed element attached to the tool tip, friction-grabbing of standardized 12 mm dowels of various lengths is enabled (Fig. 6d, f). Dowels are

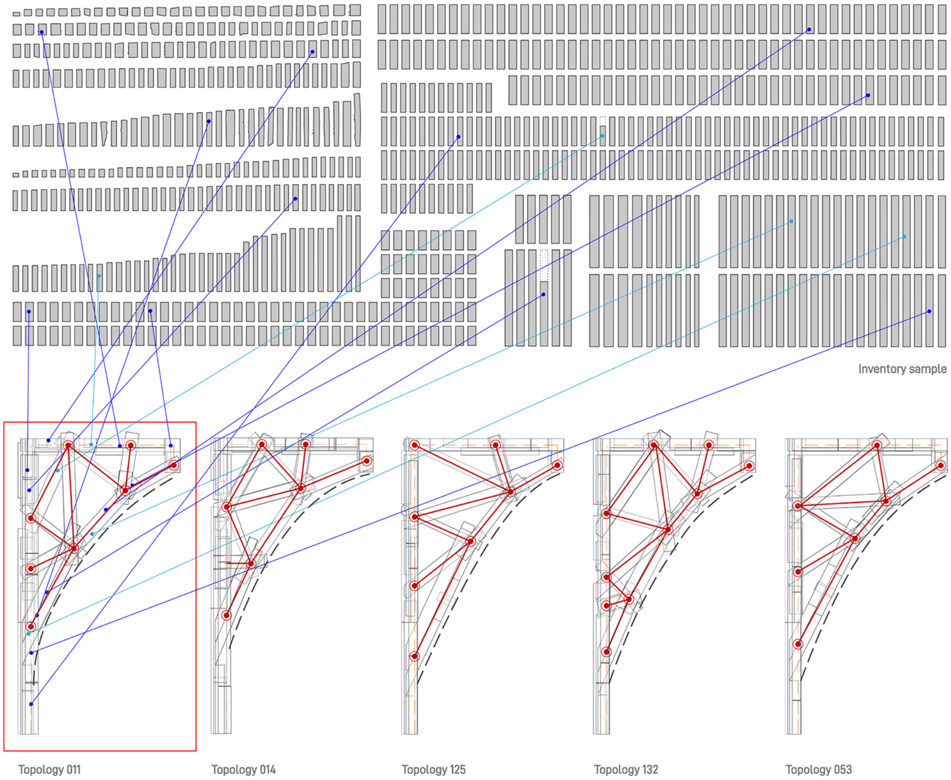

Fig. 4 Inventory, Computation of case-study one ‘frame component’, Typology iteration

Fig. 5 Case study one ‘frame’, Robotic fabrication process, End effector first generation

directly picked up from a magazine by pressing the tool tip around the dowel. The dowel is moved into position and inserted by a high-velocity pneumatic impulse, producing a press-fit joint (Fig. 6e).

Ultimately, this layered wooden assembly performs as the tension zone of a floor slab component, while earth is added on top to handle pressure forces. Both materials are geometrically connected through the irregular shapes of the elements used, enabling a friction-based interface (Fischer et al. 2025).

3 Results

The system is validated through two full-scale fabrication studies, each testing a different combination of operations, component topologies, and joining strategies. Both case studies use exclusively reclaimed timber, with no supplementation of primary timber required.

In the first case study (Fig. 7 a), 26 structural frame components are fabricated for a modular reconfigurable exhibition structure. Each component measures 3.50 m in height, 2.00 m in length, and approximately 0.30 m in thickness, assembled from reclaimed industrial offcuts and demolition timber using pneumatic wood nails. All components are assembled within a shared fabrication template. Visual inspection during and after fabrication confirms consistent alignment across repeated operations; no systematic drift or cumulative positioning error is observed across the 26 components. The components are subsequently assembled into the full-scale exhibition structure (‘ReFrame’, 2025), where they connect without requiring dimensional rework. This confirms that the tolerances achieved during robotic prefabrication are sufficient for architectural-scale assembly.

In the second case study (Fig. 7 b), two hybrid reclaimed-timber-earth floor slab components are fabricated, each measuring 4.00 m × 1.20 m × 0.35 m. Elements are stacked layer by layer following the computational design model, with wood nails providing temporary fixation and 12 mm wooden dowels providing the structural connection. Each

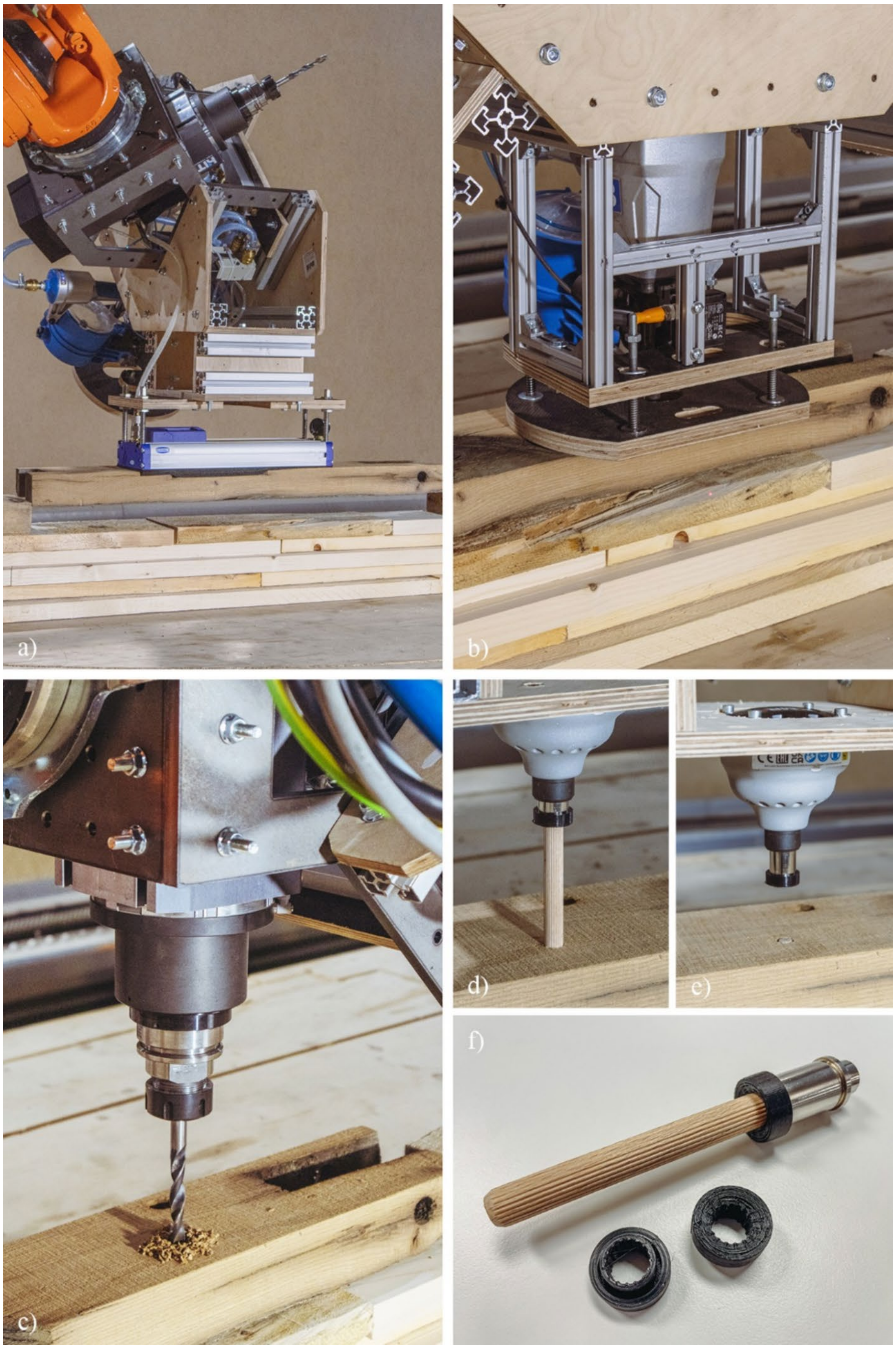

Fig. 6 Fabrication sequence: Picking & Placing (**a**), Nailing (**b**), Drilling (**c**), Doweling (**d**, **e**, **f**)

dowel is sized to connect three layers simultaneously, with its length corresponding to the combined thickness of the layers and the drilled hole depth. The closed-loop drilling sequence adjusts for surface variations before each operation using laser distance measurement, producing holes with visually consistent depth across all elements. All dowels are successfully inserted by pneumatic press-fit without manual re-seating or failed insertions, indicating that the drilling depth and diameter tolerances are within the range required for reliable friction-fit connections.

Across both case studies, the laser-based Z-offset correction compensates for the material thickness and surface variations inherent to the reclaimed inventory. Before each nailing, drilling, or doweling operation, a single distance measurement dynamically adjusts the tool's vertical position, allowing the system to operate on elements of varying thickness without manual recalibration. The offset range is not systematically recorded, but the absence of height-related operation failures across both case studies

Fig. 7 Case study one (top): modular reconfigurable exhibition structure 'ReFrame' (2025), Case study two (bottom): hybrid reclaimed-timber-earth floor slab 'ReSidual' (2026)

indicates that the sensor correction reliably accommodates the material variability of the reclaimed inventory.

The parametric Grasshopper-to-KRL workflow generates fabrication sequences directly from the computational design model, with tool paths, nail positions, and drilling coordinates derived from the digital assembly. Spatial coordination between the end-effector's multiple tool orientations is managed through embedded safe-point positions, ensuring collision-free transitions across all operations in both studies.

4 Discussion

Sensor feedback and parametric control proved central to achieving adaptive precision in both case studies. Before each operation, a laser distance measurement updates the tool's Z-offset, enabling local correction of fabrication parameters, such as drilling depth and nail gun contact distance. Rather than following a fixed trajectory, the system treats each measurement as an operational input, adjusting to the material as it is encountered. Combined with open- and closed-loop control, this approach enabled efficient transitions between fabrication modes while maintaining responsiveness to element variation and surface tolerances. In this way, the system reframes robotic automation not as a rigidly deterministic process, but as an iterative negotiation between digital instruction and physical material conditions.

This capability to accommodate inconsistent geometries extends digital fabrication beyond standardized stock, enabling the reuse of secondary timber from heterogeneous sources (industrial offcuts, demolition waste, and discarded pallets) within structural building components. By demonstrating that a single robotic platform can pick, place, nail, drill, and dowel irregular reclaimed elements into full-scale assemblies, the work aligns robotic fabrication with principles of material responsibility and circular resource use.

Despite these results, several limitations remain. The current setup relies on predefined manual element placement for picking; future iterations should integrate vision-based recognition to automate element identification and positioning. Similarly, contaminant detection and removal, currently performed manually and offline, would benefit from inline sensing. Expanding the feedback architecture to include force, geometry, and tolerance sensing would increase the system's robustness across a wider range of material conditions. Embedding machine learning models would enable predictive control, allowing the robot to perform required operations autonomously without user supervision.

More broadly, this research contributes to an emerging paradigm in which precision in fabrication emerges not from eliminating material irregularities, but from incorporating them into the design-to-production logic. The system demonstrated here represents an early instance of this approach: a robotic platform that perceives local material conditions through sensing, adapts its operations accordingly, and produces structural components from materials that conventional automation would reject.

In conclusion, this work establishes multi-functional adaptive robotic fabrication as a viable pathway toward materially responsive construction. By integrating adaptive control, sensor-driven correction, and mono-material joining within a single robotic workflow, the system produced 26 frame components and two floor slab elements from reclaimed timber at architectural scale without metal fasteners or adhesives. The results demonstrate that circular construction with non-standard materials is not only computationally designable but robotically fabricable, offering a reproducible model for resource-efficient architectural practice.

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