

AR-Driven Reconfiguration of a Triangular Wood Shell

Designing from a limited stock of elements

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Abstract. This research introduces an Augmented Reality (AR)-assisted design-to-construction framework for creating reconfigurable wooden shells from a predefined set of triangular panels. Addressing the need for adaptable and sustainable building systems, the framework facilitates the disassembly and reuse of structural components, reducing waste and enabling flexible responses to changing requirements. The AR interface enhances the design and assembly processes, allowing users to visualize and manipulate configurations in real time. By providing intuitive guidance, it empowers both expert and non-expert participants to engage actively with the iterative design process. The system's modular joining mechanism supports rapid adjustments during assembly, ensuring accurate panel placement and preserving the integrity of components for future reuse. Experiments demonstrated the framework's ability to create dynamic structures capable of evolving over time while also improving assembly efficiency and collaboration. By combining modular construction principles with AR technology, this approach promotes adaptability, reusability, and material efficiency. The research underscores the potential of blending physical and digital workflows to address sustainability challenges in the architecture, engineering, and construction (AEC) sector, advancing the development of structures that can respond to changing needs while minimizing environmental impact.

Keywords. Stock-Based Design, Human-Computer Interaction, Reconfigurable Structures, Augmented-Reality, Adaptive Design, Timber Shells, Modular Construction

1. Introduction

1.1. BACKGROUND

The drive to reduce waste and reuse building components underscores a critical challenge in contemporary architecture: the need for flexible design approaches that facilitate disassembly and reconfiguration. A promising strategy to achieve these goals is the adoption of Design for Disassembly principles. Traditional Japanese joinery offers valuable insights into such approaches, emphasizing reversible joints, modularity, compositional flexibility, and structural integrity despite standardization (Zwerger, 2012). These principles provide a foundation for sustainable construction practices by enabling the reuse and adaptation of components while preserving their integrity.

Building on this foundation, this research focuses on the construction of reconfigurable timber vaults using a finite set of triangular panels. The developed construction system follows the principle of “form follows availability” (Brütting, 2019), emphasizing modularity, ease of replacement, and reconfiguration without material damage. By relying on standardized connections, the assembly process is simplified and promotes long-term adaptability. Furthermore, this paper explores the integration of Augmented Reality (AR) to enable users to rapidly explore design alternatives, evaluate their impacts, and assist them during assembly tasks. This synergy between physical and digital processes not only aims to improve assembly efficiency but also fosters reconfigurability to extend the life of building components.

1.2. STATE OF THE ART

Key challenges in working with a constrained stock of elements include limited design flexibility and issues with dimensional tolerances of non-standard materials (Pearce, 1990). Within the context of stock-based design, two contrasting design-to-fabrication strategies are commonly identified: discretization and aggregation.

Discretization starts with a predefined target shape and optimizes element placement to meet fabrication and assembly constraints (Loh et al., 2022). Examples of top-down approaches in research projects include the Wood Chip Barn (Zachary & Martin, 2016), where tree forks are sourced to create a roof truss. The tree forks were 3D-scanned, and their positions in the structure were optimized to achieve the desired truss while maximizing material efficiency. A similar approach was employed by Grangeot et al. (2024) in constructing walls through the upcycling of concrete rubble, relying on 2D stacking algorithms and robotic construction.

In contrast, aggregation follows a process-driven approach, prioritizing connection logic over a predefined shape. The final form emerges iteratively, shaped by the constraints and opportunities of the assembly process. For example, Kaneko et al. (2024) developed a system where humans and robots gradually add wooden sticks to construct a structure without a fixed plan, allowing the design to evolve organically. Similarly, the Tie a Knot project features a cooperative assembly of wooden rods by humans and robots, with the design evolving spontaneously and supported by AR (Mitterberger et al., 2022). Comparing top-down (discretization) and bottom-up (aggregation) approaches for the reuse of concrete waste, Parry & Guy (2021)

highlighted that while top-down approaches enable optimizing material reuse and project geometry, bottom-up approaches center design decisions around humans. Conversely, top-down approaches typically tend to exclude humans from the design process through fully automated workflows that give little room for integrating design modifications in real time during construction. Mitterberger et al. (2022) also describe how increasing the flexibility of a system's aggregation logic enhances the human factor by allowing for spontaneous, on-the-spot decisions.

AR has demonstrated its value in adaptive construction processes by enabling real-time decision-making and seamlessly integrating digital and physical properties, effectively eliminating the need for traditional blueprints (Song et al., 2021). AR empowers human workers to navigate and assemble complex geometric systems, such as bespoke reciprocal frame structures, by enhancing their ability to manage intricate designs (Hughes et al., 2021). The integration of AR in assembly processes not only improves productivity but also reduces the risk of errors. For example, the reconfigurable timber frame system proposed by Kunic et al. (2022) simplifies complex construction data, enabling the integration of intuitive human decision-making during assembly. By leveraging human intuition and dexterity - both critical for navigating the dynamic and unpredictable conditions of construction sites - AR-enhanced digital models underscore the benefits of material-driven processes focused on reuse, reduction, and recycling.

1.3. RESEARCH OBJECTIVE

Previous studies have demonstrated AR's potential to support design and fabrication decisions in aggregation processes with complex geometries, particularly when working with wooden elements. These studies have shown how AR can facilitate the assembly process by visualizing design configurations in real-time, helping users optimize material use, improve precision, reduce errors, and enhance communication throughout the process. Building on these insights, this research seeks to harness AR's potential to enable dynamic reconfiguration processes within stock-constrained design contexts. By focusing on a modular triangular-panel system, the study raises a key question: How can AR facilitate the adaptation of design configurations within a system defined by the constraints of a limited stock? The research examines the potential for AR to empower end-users to engage directly in the design process, with the architect acting as a system designer who defines the parameters and logic of the system. The AR interface serves as a platform for end-users to design within the predefined system, facilitating an intuitive design process. By leveraging an easy-to-use interface, end-users can focus on the spatial design task, while an underlying algorithm manages the complex geometric operations required for the aggregation of the triangular structure.

2. METHODOLOGY

2.1. CONSTRAINED GENERATION OF TRIANGLES

For this research, an integrated design interface was developed in the Grasshopper environment within Rhinoceros 7. A geometric algorithm was created to generate a set

of triangular panels based on five input edge lengths. By limiting the stock to scalene triangles with five distinct lengths, each triangle shares at least one edge length with another. The choice of edge lengths is determined by available material dimensions, design scale, and a maximum weight of 15 kg per triangle, ensuring the panels can be carried and assembled by one person. After inputting the selected edge lengths, the algorithm generates a corresponding set of triangles, with a maximum of ten valid configurations. Once the set is determined, users can select from four options in the design interface:

- Adding one panel connected to one free edge of the structure
- Adding a support panel connected to one free edge of the structure and in contact with the ground
- Adding two jointed panels connected to two adjacent free edges of the structure
- Removing one or more panels of the structure

Developing the integrated design workflow, particularly involved solving the design space associated with the first three functions. In all four cases, the user is first asked to select a naked edge on the mesh of the existing structure. Next, the algorithm looks for matching edge lengths in the stock of available panels. When adding one panel without constraints, the user is asked to choose among the matching solutions and decide the orientation of the panel while ensuring there is no collision with the existing structure. For each matching triangle, the design space results in a circle (i.e. the geometric solution is the intersection between two spheres as illustrated in Figure 1a). In contrast, when adding a support panel or two jointed panels, the design space is finite as it is limited to a few points (i.e. the geometric solution is the intersection between two spheres and the ground plane for support panels or between three spheres for two jointed panels as illustrated respectively in Figure 1b and 1c). In the specific case of adding two panels, the number of solutions in the design space is highly dependent on the angle between the two consecutive selected edges and varies for each combination of edge lengths. Moreover, note that joining two adjacent edges of the structure with only one panel is almost never possible unless the angle between those two edges exactly matches the angle between the corresponding edges of one of the triangles in the set.

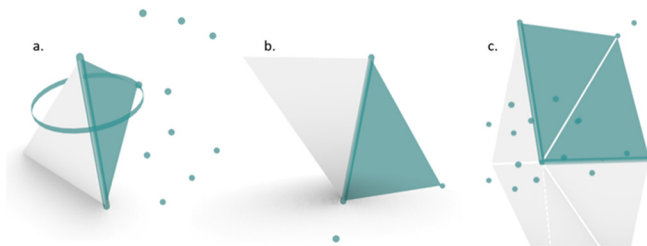


Figure 1: Example of design spaces when adding one triangular panel (a), one support (b), or two panels (c). Each sphere represents a potential location for the free summit of the added triangles.

2.2. JOINT OPTIMIZATION

The triangular panels are connected with 3D-printed plastic hinges (two or three depending on the edge length) that can be tightened with a screw to fix the panels with the desired orientation (between -90 and $+90$ degrees). This system is aimed to facilitate the assembly and disassembly of the elements through the successive reconfigurations of the wooden shell. The printing material, polyethylene terephthalate glycol reinforced with carbon fiber (PETG CF), is selected for its enhanced strength, flexibility, and durability, making it suitable for accommodating torsional forces and withstanding repeated assembly and disassembly cycles without damaging the joints.

The hinge position is automatically optimized based on the generated set of triangles. The algorithm maximizes the distance between the hinges (Figure 2). For each edge length, the solver finds the most restrictive joint area across compatible triangles (Figure 2a) and avoids overlapping connections from different edges (Figure 2b) to find the optimal solution (Figure 2c). The process is repeated for the five edge lengths of the set. Next, the corresponding joint area is applied to each triangle (Figure 2d). Ultimately, the hinges are positioned as far apart as possible, within the connection area, and the corresponding position of the drilling holes is automatically exported, along with the panel contour, for CNC machining (Figures 2e and 2f).

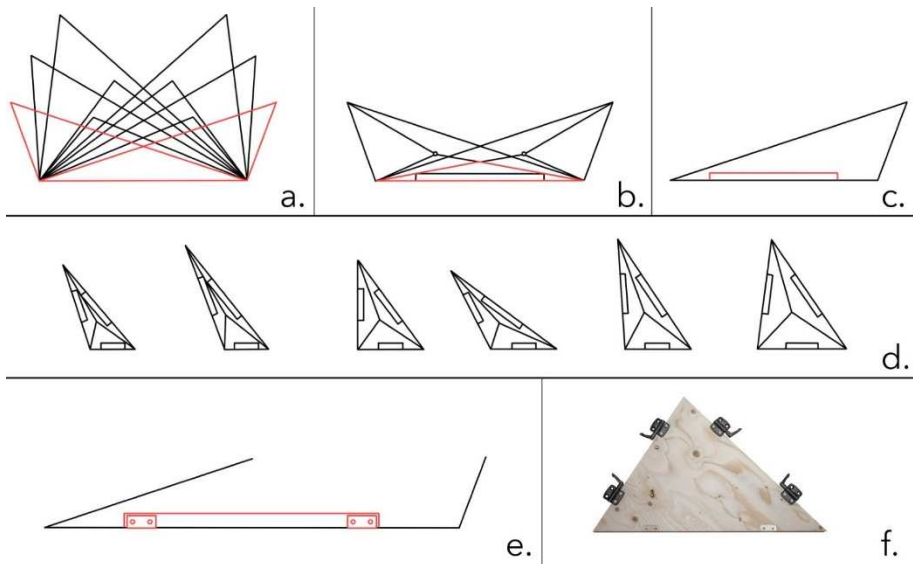


Figure 2: Optimization process for maximizing the distance between hinges for each edge length while ensuring compatibility with all triangles from the generated set.

2.3. AUGMENTED-REALITY INTERFACE

A pair of HoloLens 2 is used as head-mounted displays (HMD) for multi-user collaboration. The connection between the digital twin and the HMD is performed through Fologram's Grasshopper plugin (Fologram, 2024). In addition, the user interface is developed in Unity 3D by relying on the Rhino.Inside framework to

facilitate event handling and enable fast response time. Panels and joints are created through Grasshopper according to user actions and stored as a JSON file, which is parsed in Unity and Rhino to visualize the structure.

The developed interface allows users to interact with the holographic structure at full scale. By clicking on a panel with their fingers, the closest naked edge is selected (Figure 3a). Users can choose between four actions through a control panel to reconfigure the structure (Figure 3b): adding one free triangle, adding one support triangle, adding two adjacent triangles, or deleting one triangle. When adding triangular panels, the design space is represented by spheres with each sphere representing a potential location for the free summit of the added triangles (Figure 3c). By touching the spheres, users can explore the different design possibilities in accordance with the geometrical constraints given by the stock of available elements. Furthermore, when adding only one panel on a free edge without additional constraints, an interactable ring allows users to change the rotation of the panel (Figure 3d). Overall, this setup allows for seamless interaction between the physical and digital environments, ensuring real-time updates and intuitive manipulation of the design configurations.



Figure 3: Users can interact with the structure through the AR interface (a), and use a control panel to choose between four actions (b), and explore the design space (c and d).

3. Experimental results

The developed interface was tested through several experiments involving one or two end-users working alone or together. Two sets of edge lengths were tested (Set A = 20, 30, 40, 50, 60 cm; and Set B = 50, 60, 70, 80, 90 cm). With Set A, only seven valid scalene triangles out of the ten possible distinct combinations could be made (Figure 4a) while with Set B, all lengths combinations returned valid triangles, resulting in a set of 10 elements (Figure 4b). The good functioning of the workflow was first evaluated only through virtual assemblies with both sets of triangles. However, it was decided to proceed only with set B for physical experimentations as it generated less waste after nesting the triangles on standard wood panels (Multiplex Pappel, 4mm thickness, 440 kg/m³) and produced wider solution spaces resulting in an overall less constrained design process.



Figure 4: The number of triangles that can be generated varies with the chosen set of edge lengths (Set A: 20, 30, 40, 50, 60cm; Set B: 50, 60, 70, 80, 90cm edge length)

Two mock-ups were constructed by relying on a previously developed design-to-fabrication algorithm to export fabrication data (Authors, 2022). The first assembly consisted of 5 pieces ranging from 2,5 to 3,6 kg, with the purpose of assessing the ease of assembly of the panels by hand with AR guidance as well as the performance of friction-based hinges under human-scale conditions. For the second assembly, a half-scale prototype was built using a total of 7 panels to further experiment with the design interface and evaluate the benefits of AR in supporting humans in exploring complex design solution spaces. Different spatial configurations were explored with this prototype as illustrated in Figure 5.

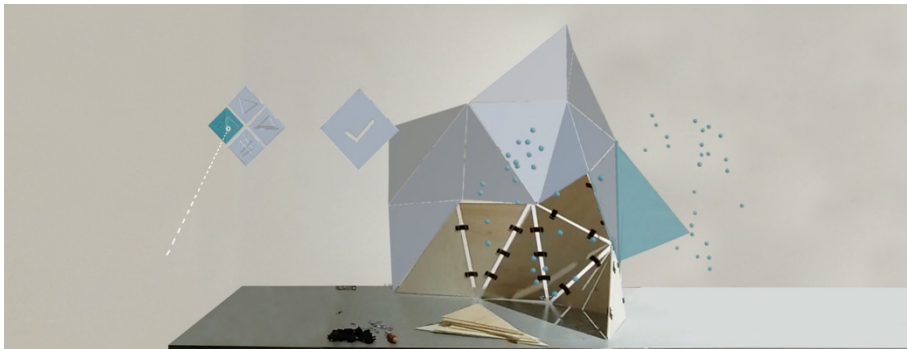


Figure 5: Physical assembly with the AR-overlay showcasing the design space and the interactive user interface (captured with the HoloLens 2).

4. Observations

4.1. STOCK-CONSTRAINED DESIGN FOR TRIANGULAR SHELLS

Initial virtual experiments with the seven triangles of Set A revealed challenges in designing structural shells with such a limited set of components. While adding a single panel to a free edge is straightforward, adding two adjacent panels introduces significant constraints and can lead to undesirable outcomes if a specific target shape is sought. However, adding two adjacent panels is essential for closing fan-shaped assemblies, where multiple triangles share the same vertex (Figure 6). In this context, the size of the solution space greatly influences the outcome, with results either aligning closely with the target surface (Figure 6a) or creating protruding spikes (Figure 6b).



Figure 6: Closing fan-shaped assemblies with two adjacent panels will lead to coherent (a) or eccentric (b) results according to the size of the solution space.

Further calculations were performed to investigate the correlation between the number of solutions for attaching panels and the angle of a panel. It showed that the solution space for two adjacent panels depends on the selected edge lengths and the angle between them, as illustrated in Figure 7. The color-coded matrix for Set A (upper) shows a maximum of 36 solutions per configuration (dark green cells), with an average of 11. For Set B (lower), the number of solutions ranges from 50 to 72 configurations (blue cells), with an average of 31. However, both matrices suggest that designers should prioritize angles between 45 and 90 degrees for closing fan-shaped assemblies.

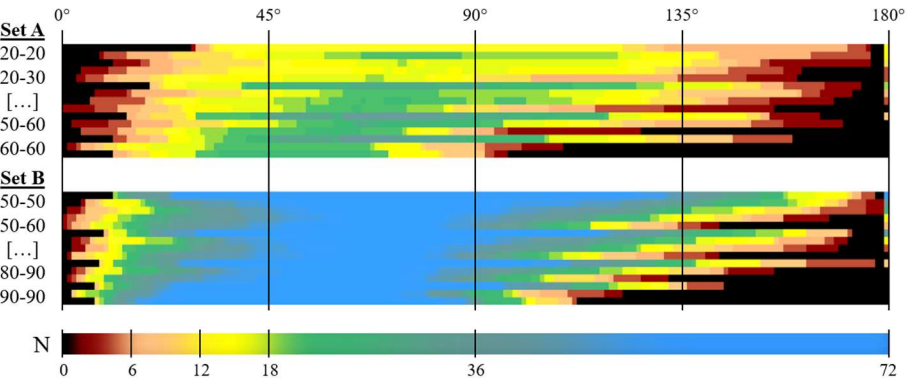


Figure 7: The number of solutions (N) for adding two adjacent triangles varies according to the length of the selected edges (matrix rows) and the angle between them (matrix columns).

4.2. AUGMENTED DESIGN AND CONSTRUCTION

The integration of AR in design and assembly processes proved effective for real-time discussions and visualizing design variations. The intuitive interface enabled clear communication, allowing users—particularly non-experts—to quickly grasp the system's functionality and focus on spatial configurations rather than technical challenges. Users could immediately assess the structural and spatial feasibility of designs, identifying material conflicts or alignment issues before physical assembly. The interface provided valuable guidance on available stock and valid configurations, with interactive elements like spheres and rings simplifying navigation through the solution space.

AR also enhanced the assembly process by displaying full-scale 3D models, ensuring correct panel selection, and simplifying positioning. It increased on-site independence by eliminating reliance on external tools or additional personnel. In cases with limited valid configurations, AR provided precise guidance, accelerating and improving assembly accuracy. Initial challenges, such as latency and user fatigue from prolonged headset use, were addressed by optimizing event handling in Unity and highlighting the need for more ergonomic devices.

5. Conclusion

5.1. ACHIEVEMENTS

This research introduces an AR-assisted framework that places humans at the center of the design and construction process for reconfigurable wooden shells. By enabling real-time interaction with a constrained stock of triangular panels, the system empowers users—both experts and non-experts—to intuitively explore design possibilities and actively engage in assembly tasks. The AR interface fosters collaboration and decision-making by providing real-time feedback on available materials and valid configurations, allowing users to directly shape outcomes without relying solely on predefined algorithms. This human centred approach ensures adaptability, material reuse, and sustainable construction practices while maintaining the flexibility and creativity inherent in the design process.

5.2. OUTLOOK

The integration of AR in reconfigurable construction systems offers significant potential for advancing sustainable building practices. Future research could explore scaling the modular system to larger, more complex structures, incorporating structural considerations such as load distribution and material performance. Refining AR interfaces and algorithms will enhance user autonomy, facilitating more efficient design and assembly. Additionally, optimizing AR devices for long-term use and testing the system under varying environmental conditions will improve reliability. As circular and stock-based design principles gain traction, it is crucial to develop workflows that allow for unpredictability and leverage human agency. AR and other human-centred digital technologies can play a key role by enhancing adaptability and supporting intuitive decision-making in design and assembly processes.

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ChatGPT (OpenAI, 2024) was used to refine the wording of paragraphs.