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AR-enabled circular construction of a computationally designed reclaimed wood shell structure.

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Abstract

The research presents a design-by-availability case study focusing on utilizing wood waste from secondary material streams in combination with augmented reality (AR) for complex three-dimensional assembly. It realized a double-curved shell structure using irregular reclaimed elements, seamlessly integrating digital design principles with manual craft skills. The research exemplifies a digital upcycling method for wood waste, turning small-scale wood scraps into more significant structural components. By integrating wood-nailing principles into a computational design framework and issuing assembly instructions through AR technology, the study demonstrates a design-to-build approach centered on locally available materials, showcasing the potential of digital craft and circular construction practices.

Keywords: reclaimed wood, augmented reality, wood nails, circular construction, computational design, shell structure, recycling, reuse, timber, design-by-availability, design-to-build

Introduction

Developing ecologic and sustainable structures is fundamental for a greener future in architectural innovation and circular construction. This paper explores such practices through a case study focused on constructing a pavilion for a local festival in Karlsruhe, Germany. The aim was to build a geometrically complex shell structure from reclaimed wood elements, demonstrating the potential of secondary used wood as a construction resource enabled by augmented reality. This construction approach contributes to the extended sequestration of embedded CO2 within the building stock by preventing reclaimed wood from incineration, effectively serving as a carbon sink. A student group comprising 20 participants united manual skills with digital tools and computational design principles to realize this pavilion. This case study suggests an AR-supported digital craft workflow to enable collaborative assembly.

Previous research projects, like the Re/Place pavilion, have demonstrated how digital tools can enable construction workflows and complex results with repurposed timber [1]. Demonstrators like the Steampunk pavilion for the Tallinn Architecture Biennale have shown how AR can help assemble geometrically complex shapes or how mixed reality applications can improve the efficiency of human construction teams in rapidly fabricating complex structures [2]. Figures like G. Jahn have researched and analyzed the opportunities for design and construction practice and concluded that the value of mixed reality fabrication lies in adapting digital models to the complexities of construction sites, including skilled or unskilled handcraft, vernacular architecture, and local materials [3]. After the peak of digitalization, more attention is paid to craftsmanship, local material systems, and the utilization of digital design thinking [4]. AR-enabled bricklaying is an example of how digital technology can enhance manual skills. AR is used to help with the position of bricks, while manual craft techniques were indispensable [5]. Most projects that utilize AR in construction rely on similar methodologies: assembling prefabricated pieces to match a distinct (digital) geometry and position of a 3D model. The shown research distinguishes itself by leveraging reclaimed wood elements without prior or additional geometric modifications for assembly connectivity to create a structural and aesthetic design.

Figure 1: Nail-It pavilion for 'Das Fest' festival in Karlsruhe, exterior and detail.

Figure 2: The structure of the nail-It pavilion for the 'Das Fest' festival in Karlsruhe.

Methodology

This study embraced a design-by-availability approach, focusing on using reclaimed wood waste for circular construction. The design process was initiated with a top-down strategy, integrating bottom-up requirements such as material properties, structural principles, construction logic, and ease of transport and assembly. Augmented reality bridges the gap between computational design results and crafts-based assembly to realize this shell structure pavilion. Through the convergence of manual and digital craftsmanship, the goal was to create a proof-of-concept demonstrating the seamless integration of diverse individuals, each possessing unspecified knowledge and skill sets, into the construction process facilitated by augmented reality instructions.

Reclaiming wood waste and reconditioning constituted the initial phase, carefully sorting and cleaning the reclaimed materials. This process included the manual removal of foreign objects such as nails and screws, as well as the trimming of broken parts and sanding of rough edges to avoid potential injuries. The primary sources of reclaimed wood were single-use or broken EPAL pallets and boards with comparable thicknesses but various lengths and widths. Elements were selectively sorted during this manual process to meet minimum length and thickness requirements. Due to the structural requirements, the minimum length was set at 30cm and the minimum width at 8cm.

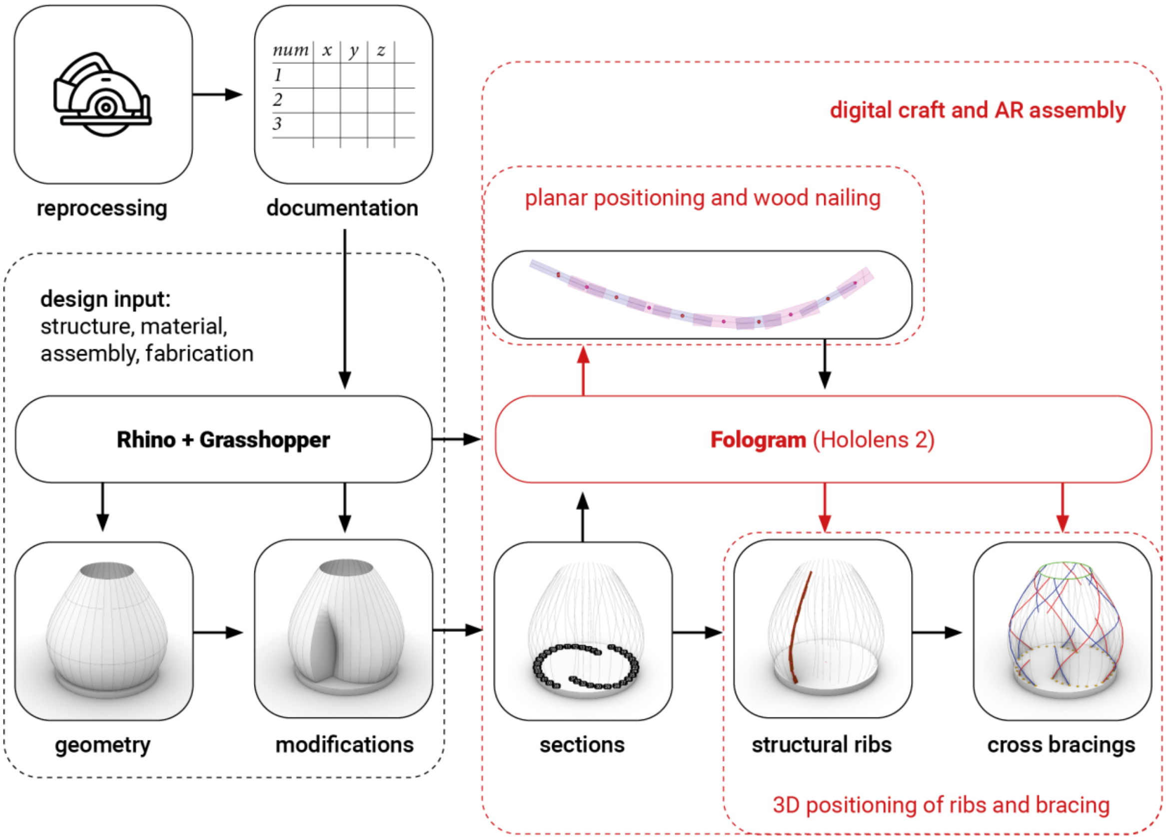

Figure 3: design workflow and structural elements

Figure 4: reclaimed wood, digital parametric design, wood nailing, collaborative AR assembly (left to right)

Subsequently, each reclaimed wood piece underwent manual documentation of its dimensions using a physical template to accelerate the process. All dimensions were recorded in an Excel sheet alongside unique identifying numbers for each reclaimed element. These numbers were then assigned to the wood pieces using an InkJet printing gun, streamlining the identification process during assembly.

Unlike conventional inventory-based optimization approaches, this study prioritized availability over inventory buildup. To enhance workflow efficiency, documented wood elements were streamed into the ongoing design and fabrication process as soon as they were documented to accumulate a fully documented inventory. The individual section curves [Fig. 3] derived from the overall pavilion geometry dictating the shape of each rip. Once the algorithm developed in Rhino3D and Grasshopper determined that enough pieces were reported to assemble one structural rib, a 3D model was generated. The developed design tool was used to monitor the documented wood pieces and distribute them along the individual section curves, considering structural specifications such as the overlap of the wood boards and the distance of wood nails to the edge. Each of the individual ribs consists of three connected layers of wooden elements, with an overlap of at least 10cm between each other to ensure structural integrity. A flexurally stiff connection between the individual wooden elements was created by arranging at least three wooden nails in a triangular configuration, providing a minimum distance of 30mm from the edge and between each other to ensure the required rigidity [Fig.7]. To create a statically determined self-supporting shell structure, all rips were connected at the base by horizontal supports and a pressure ring on top. The existing 3D model was further developed in Karamba, a plugin for Rhino3D, resulting in a structural model used for the structural analysis. The same model was used to calculate the arrangement of the necessary diagonal bracing to stabilize the structure and minimize the elements required to withstand horizontal forces such as wind.

Augmented reality technology, combined with Hololens 2 glasses, Rhino/Grasshopper, and the Fologram plugin, facilitated the assembly process. A 1:1 scale digital model of each rib was projected onto the ground, allowing for precise identification and arrangement of reclaimed wood elements [Fig. 5]. The digital model was a template for positioning each piece during this first manual construction phase. When the position of two elements was found, a nail gun was used to shoot wooden nails according to the positions provided by the digital template. According to structural implications, this template provided a rectangle to position the wood nails, in which at least three wooden nails were positioned, which were structurally necessary [Fig. 6]. Despite careful planning, some wood pieces broke during nailing and required replacement. A solution proposed to mitigate this issue was using nails with heads, minimizing the splitting of individual woods due to the geometry of the nail tip and head, which proved successful. After this assembly process, all 36 structural ribs were manufactured flat to the ground. When one rib was completed, a unique identifying number was assigned to monitor its later position [Fig.6].

In the final assembly phase of the project, AR played a pivotal role in placing the fabricated structural ribs. The position of each rib was projected into the AR environment, providing clear guidance on where to place them. Once all the ribs were positioned, AR provided digital curves as guidelines to indicate the cross-bracings' position. These reinforcements were crucial for the pavilion's structural integrity and AR-enabled intuitive assembly opportunities. Reclaimed wood elements realized cross bracing.

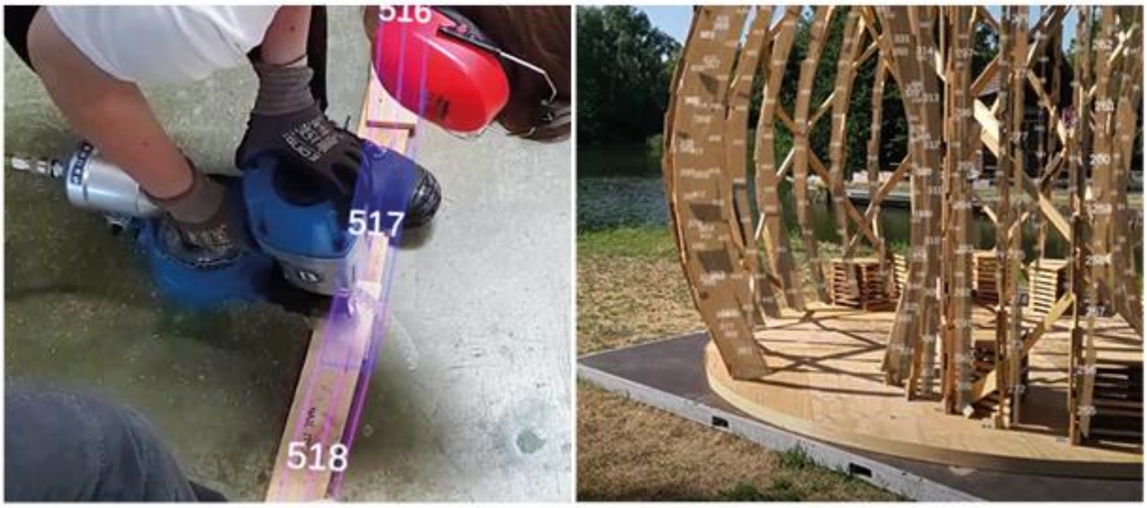

Figure 5: positioning and nailing of reclaimed elements according to digital template using AR (left) virtual and physical model of the final structure (right)

Results

The study results demonstrate the successful integration of computational design and manual assembly, facilitated by augmented reality, in constructing a complex 3D shell structure. With 824 individual reclaimed wood elements, the structure was erected precisely and efficiently, underscoring AR's potential in complex construction scenarios.

AR provided clear guidance for all participants, enabling the practical construction of the pavilion while adhering to predetermined structural requirements such as element overlap, wood nail positions, and cross-bracing placement. Despite variations in component angles, overlaps, and positions, AR offered real-time visual feedback, eliminating the need for on-site measurements or fully automated robotic prefabrication. Participants accessed assembly instructions and structural details directly through the AR interface, enhancing efficiency and minimizing errors. Adopting a design-by-availability approach further streamlined the project, which a team of 20 participants completed within four days.

The study underscores the advantages of integrating AR technology and the design-by-availability approach in construction projects. AR facilitated step-by-step instructions for participants with varying skill levels, allowing selective use of different informational resources as digital construction templates. These resources included outlines and numbered tags of reclaimed wood elements, positions of connecting wood nails, individual rib layers, and a rendered 3D model of the finished structure. Augmented reality bridged the gap between computational design and craft-based assembly, enhancing workflow efficiency. Parallelizing operations into reclaiming, documentation, and multiple assembly teams further optimized operations. The final shell structure comprised 824 pieces forming 36 structural ribs and cross-bracings, measuring 5.0 by 5.0 meters and 4.5 meters in height. Removable furniture crafted from reclaimed wood also provided seating, adding a sustainable touch to the project's completion.

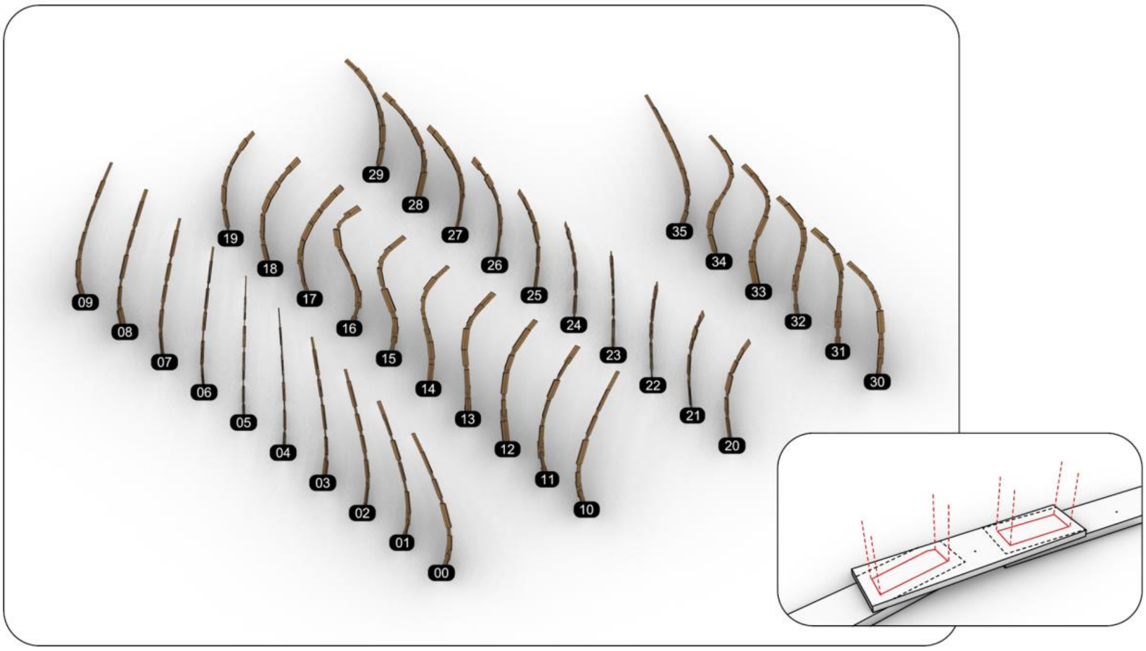

Figure 6: digital model of all individual structural ribs, overlapping scheme.

Discussion

This study's discussion emphasizes the distinctive contributions and implications of using augmented reality technology and the design-by-availability approach in construction projects, particularly in comparison to established traditional top-down methodologies.

As mentioned at the beginning, previous research examples in construction have predominantly focused on manufacturing necessary components based on a 3D model rather than incorporating reclaimed materials through a design-by-availability approach [Fig.3]. This research, however, reversed this process, demonstrating the feasibility and advantages of integrating reclaimed pieces alongside AR technology. A noteworthy characteristic of the design-by-availability approach adopted in this research pavilion is its elimination of the need to maintain a complete inventory before starting with any assembly. While many matchmaking or reuse strategies require inventory accumulation, the design-by-availability approach bypasses this requirement, resulting in a more streamlined and efficient process.

Although this approach offers significant potential for future applications by reducing construction time and resource utilization, it may limit optimization in other aspects, such as structural performance or material efficiency. Nonetheless, there is potential for synergy by combining the design-by-availability approach with small inventories, which can be optimized to enhance efficiency and performance further. Utilizing AR as a digital construction manual rendered the process approachable and accessible for participants with various constructive knowledge and manual skill sets. All relevant and necessary information was available and digitally communicated. This advancement can reduce reliance on printed construction plans, streamline processes, and minimize environmental impact over time.

Regarding AR implementation, referencing the 3D model in AR functions effectively. However, occasional issues were observed with AR glasses losing track, particularly in crowded environments. Additionally, tolerances within the structure were measured as high as 5cm. This pavilion was designed to accommodate these tolerances, effectively mitigating potential issues.

Lastly, a global referencing system enabled multiple workers to collaborate simultaneously on the construction site, enhancing productivity and efficiency. Overall, the integration of AR technology and the design-by-availability approach represents a promising advancement in construction methodology, offering significant benefits in terms of efficiency. The project is an initial step towards integrating AR and crafts-based assembly of irregular reclaimed pieces, demonstrating its feasibility within a teaching environment by instructing an untrained workforce to execute a complex assembly procedure.

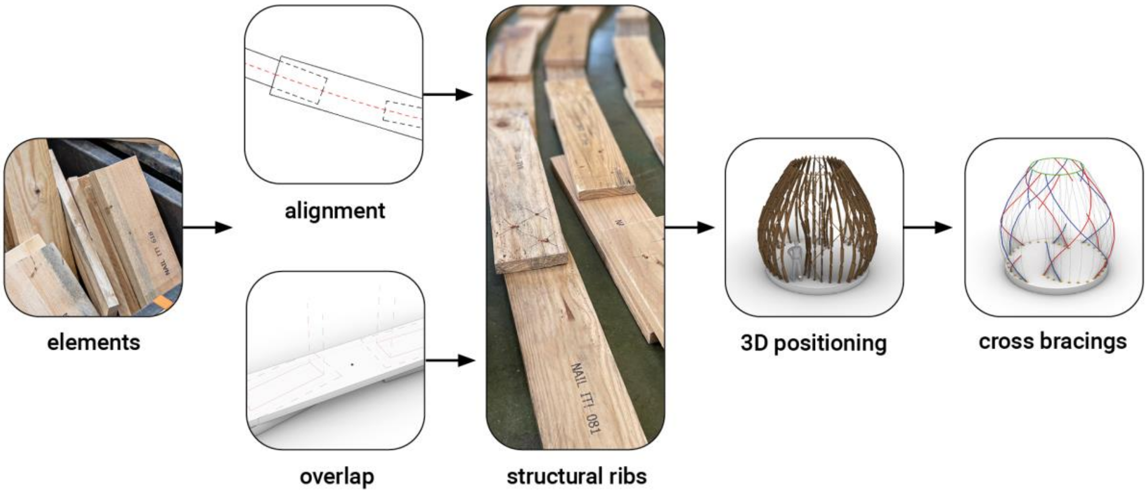

Figure 7: from single elements to a designed structure

Conclusion

This study has provided insights into applying augmented reality technology and the design-by-availability approach in construction, particularly within sustainable architecture and circular construction practices. The research pavilion [Fig.8] serves as a proof of concept and a feasibility test for these methodologies, illustrating how innovative design and assembly techniques, paired with manual craftsmanship, can facilitate the digital upcycling of wood waste.

The principal findings of this study underscore AR's transformative potential in facilitating the efficient and accurate assembly of complex structures using reclaimed materials. By providing workers with accessible tools and real-time guidance, AR has broadened access to construction processes, reducing dependence on specialized expertise and high-tech fabrication machinery.

The significance of this research pavilion lies in its embodiment of digital upcycling methods for wood waste. The pavilion reimagining traditional manual construction processes and leveraging digital tools demonstrates how reclaimed materials can be repurposed to create innovative and environmentally conscious architectural structures. Numerous avenues exist for further research and development in facilitating AR for sustainable architecture and circular construction. AR's potential for circular assembly warrants exploration, particularly in optimizing efficiency and reducing waste by gathering real-time data on construction progress and providing instant feedback to the workforce through real-time optimization and error detection algorithms. Additionally, investigating human-robot collaboration with AR can revolutionize construction practices, maximizing productivity and precision by leveraging the strengths of both human workers and robotic systems.

In conclusion, this research pavilion represents an alternative design-by-availability workflow toward more sustainable and circular construction practices. Adopting digital upcycling methods and utilizing AR technology showcases the potential for a more environmentally conscious and efficient built environment. It further explores the material and process-informed design expression of short timber leftovers, resulting in a fine grain that articulates a structure of high visual detail.

Figure 8: Nail-It pavillon for DasFest festival in Karlsruhe, structure

Acknowledgements

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