Mapping Human Agency in the AR-Enabled Co-Production of an Urban Community Podium

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Keywords: AR-Enabled Production, Timber Dowel Structures, Human-Machine Agency , Urban Communities, Co-production.

The application of Augmented Reality (AR) in construction is transforming how non-expert users engage with complex assembly processes, with its potential to foster broader community involvement in urban space production remaining underexplored. This paper presents an integrated framework that incorporates AR-enabled phygital instructions with timber dowel structures, facilitating the active participation of non-experts in the design-to-production process of an urban community food podium. By leveraging AR and computational design, the system bridges the gap between expert and non-expert users, enabling wider participation in the construction process while maintaining precision through robotic fabrication and step-by-step digital guidance. Tested within a graduate-level course and showcased at a public event, the project aims to empower community members to engage in production and assembly, offering insights into participatory urban design and co-production. The results demonstrate the capacity of augmented fabrication to enhance human agency, making complex construction tasks accessible and collaborative, and paving the way for resource-driven, community-enabling urban developments.

INTRODUCTION

The integration of Augmented Reality (AR) and robotics into construction and design processes is reshaping how designers and builders engage with digital information on-site, creating new possibilities for interaction in the physical world. This paper maps the role of human agency in the co-production of an urban community food podium, emphasizing the use of AR technology to guide and empower non-expert participants throughout the building and assembly process. Additionally, the paper introduces site-specific factors alongside an integrated computational design system. The project develops an AR-enabled framework that combines computational design, robotic fabrication, and real-time human collaboration to construct a free-form timber dowel structure. The study aims to establish a replicable workflow that fosters active community involvement while maintaining precision and efficiency through digital tools.

As assembly processes become more complex in construction, several technologies are being developed to support the production of free-form and non-standard structures. Since its early development, augmented reality is applied to complex assemblies, providing real-time information by overlaying digital instructions onto the worker's field of vision, improving efficiency and reducing errors [1]. With the development of computational design tools and the introduction of numerically controlled machines such as CNC machines, laser cutters, 3D printers, and later industrial robots in assembly lines, the importance of interactive and user-friendly instructions continues to increase. Augmented reality, as a medium between the numerical world and the real world, delivers essential information to human operators at each step of the assembly process.

While AR has mostly been tested in professional settings where participants already have knowledge about the process and production, its potential to include non-expert designers and builders remains unexplored. Using holographic instructions, AR helps overcome the difficulties of interpreting traditional 2D drawings, making it easier for non-experts to participate. The system, with mapped human agency, is based on the hypothesis that AR makes specific parts of information accessible, allowing non-expert community members to understand and apply them effectively. This approach offers a solution for increasing community involvement in shaping their built environment, addressing a key barrier to broader participation in urban spaces.

This paper examines the role of human agency in the augmented co-production of an urban food podium, emphasizing the pivotal role AR technology plays in facilitating the preparation and assembly processes for non-expert users. A resource and performance-driven design-to-production and assembly framework is developed and prototyped within a graduate-level course at Texas Tech University, Huckabee College of Architecture (TTU HCoA) in collaboration with the South Plains Food Bank (SPFB). While the design is tailored to meet site-specific conditions, the production process is mapped to establish a replicable workflow that promotes active community involvement throughout the building process. The project employs a timber dowel structure as the material system, generated through an integrated design-to-production framework. This framework includes the computational generative design of the timber-dowel system, interactive AR-assisted timber cutting, robotic milling, and AR-enabled assembly, all facilitated through customized step-by-step assembly instructions.

BACKGROUND AND CONTEXT

This contextual research background to this work is threefold: timber dowel systems, augmented reality (AR), and AR's role in fabrication and co-production. In wooden structural systems, the arrangement of timber and dowel elements has been explored across various configurations, including free-form shell structures fabricated with timber-dowel elements, dowel-laminated slabs, and cooperative robotic fabrication processes [2]. Related research has focused on optimizing timber structures using computational methods like genetic algorithms to estimate dowel quantities for joints, which helps reduce costs [3]. Other approaches, such as mixed-integer nonlinear programming, have been applied to enhance structural efficiency [4], and hybrid dowel connections with bonded steel plates have been studied to improve structural properties [5].

The utilization of augmented environments has been researched for its ability to bring multi-layered models with sequences of production and assembly as real-scale construction guides. AR assembly offers significant benefits in on-site scenarios, particularly in urban production contexts where space and logistical constraints pose challenges [6]. Human agencies, informed by holographic guidance, enhance communication between designers and builders by providing interactive, real-time feedback, contrasting with conventional 2D drawings and instructions[7].

Augmented production environments utilize holographic mapping to provide a scaled, contextualized, and informative experience within real-world settings[8, 9]. Augmented reality (AR), as part of a mixed-reality experience, integrates digital information into the physical world through devices and applications[10]. In digital fabrication, AR applications enhance human-computer interaction and data sharing by offering holographic instructions and digital guidance for tasks like measurements, alignments, and step-by-step assembly during complex productions[7]. The construction industry has explored AR across various applications, including interfaces like Fologram for building vaults[11], bricklaying assembly[6, 12, 13], and specialized tasks such as form-working, weaving structures[14], and timber construction[15].

AR-enabled fabrication and assembly integrate user-defined information directly into the physical environment, improving timber structure production by offering precise assembly sequences and measurements. This interactive approach also allows operators to tailor their workspace to specific needs, with digital twins providing real-time annotations that guide informed human intervention throughout the process. Additionally, the mixed-reality environment strengthens connections between designers and fabricators, moving past traditional 2D shop drawings and encouraging engagement from a wider range of participants, supporting local and community involvement.

This research highlights how integrating low-tech and high-tech methods in community-focused projects can expand human agency in co-production using in augmented environments. By integrating AR and robotic fabrication with manual wood working, the project demonstrates how emerging design-build technologies can be made accessible and inclusive, enabling community members to participate actively regardless of their technical expertise. More details are further explained in section 3.3.

METHODOLOGY

The main objective of this study is to create an open system for design and production, enabling communities with little or no knowledge of augmented fabrication and computational design to engage with the integrated design-to-production system at various levels. Experts are defined as those with specialized knowledge in design, engineering, or fabrication, while non-experts refer to community members with limited or no technical background in advanced manufacturing. Community participants in this project, including those directly or indirectly connected to the South Plains Food Bank, have informed our conceptual framework through initial interactions, with potential for deeper involvement as the project develops.

The methods in this research focus on mapping human involvement at two levels—experts and non-experts—emphasizing the engagement of non-experts in both the design and production phases through an AR-enabled co-production system. This system allows non-experts to collaborate with experts across four interconnected phases: Design and Parametrization, Performance and Analysis, Human-Machine Co-Production, and Material Passport (Figure 1). AR and robotic systems guide physical assembly, enhancing non-expert participation, while the Material Passport tracks resources and repurposes waste materials. This approach redefines the building process as a collaborative, educational experience, merging digital precision with active human agency. By integrating AR technologies, sustainable design, and community-driven processes, the project addresses social challenges like food insecurity and community resilience, demonstrating how innovative design frameworks can transform urban spaces and foster community engagement.

By combining computational design, AR, and robotic fabrication, the process becomes more efficient and scalable, enabling community members to actively participate in construction [16, 17]. The use of digital tools simplifies complex assembly processes, allowing non-experts to contribute effectively and bridging the gap between technical expertise and community engagement[18]. Figure 1 provides an overview of the entire integrated design-to-co-production system, with established connections and feedback loops between the four main domains of the project.

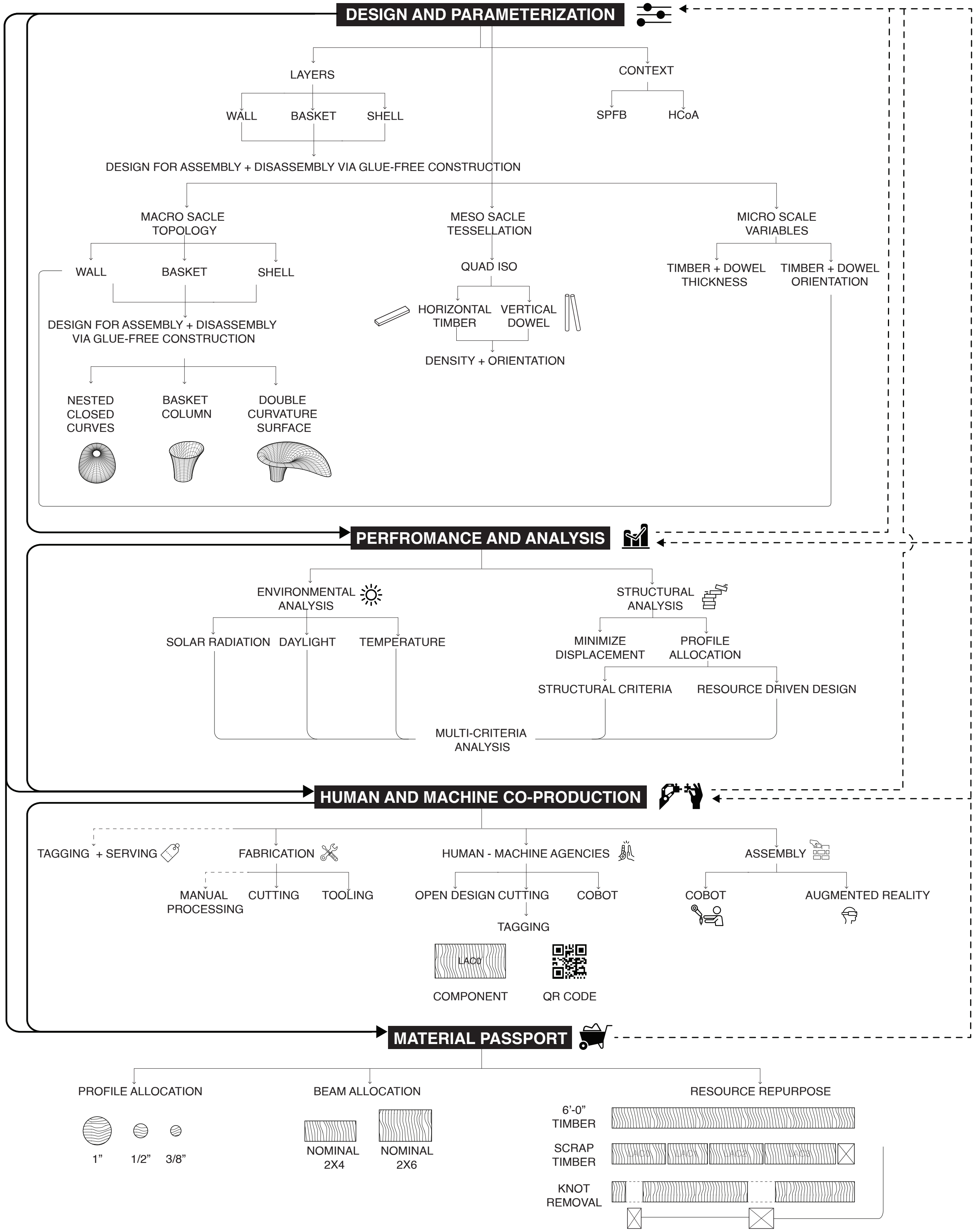

Figure 1. An overview of mapping human agency in design to co-production framework.

Design and Parametrization

The computational framework for the timber dowel system utilizes adaptive tessellation and integrates augmented reality (AR) with robotic fabrication, creating a seamless design-to-production workflow. This approach ensures flexibility and supports scalability, allowing the framework to adapt to different contexts and urban environments. Such adaptability is crucial for addressing sustainability and food security in underserved urban areas, where community-led assembly and co-production are key to building resilient, localized food systems[19]. By integrating these design-to-production technologies, the project supports the creation of self-sustaining infrastructures that mitigate the impacts of food deserts, which disproportionately affect marginalized communities in the Lubbock context[20,21].

The design and parametrization phase establishes the project within its specific context, defining both the design outcome and the parameters needed to meet contextual requirements. The cases designed and prototyped here are creating a gathering space for the SPFB and a shading structure for the TTU HCoA. In each case, the primary goal is to design for assembly and disassembly of a glue-free timber-dowel structure. This approach shapes the design to fit community needs and emphasizes engagement and hands-on participation, reinforcing the connection between the community and their built environment.

The design process unfolded in three subphases—macro, meso, and micro scales. At the macro scale, initial shape explorations identified three potential configurations for the timber-dowel system: a wall, a basket column, and a shell. At the meso scale, the structure is generated based on the guiding (poly)surfaces of these forms, using U curves to guide the generation of the whole timber dowel system. Two distinct curve typologies are identified based on surface properties. The initial computational framework for the Timber Dowel System was developed at the meso scale using poly-surfaces as input geometry, with adaptive tessellation systems to address various functional and contextual requirements. The model is later updated, allowing for a data-driven design process, adaptable to environmental and structural needs. Key parameters include timber orientation, allocation, and the use of a single guiding surface with adaptive features, enabling a high degree of customization within the design space.

To ensure structural integrity, the timber dowel system was developed using a Running Brick Bond tessellation, creating overlapping layers where each timber connects with four others in adjacent layers. Initially, UV isocurves of the surfaces are defined, and isocurves are extracted at regular intervals across the surface domain to maintain the topological parallelism of the layers. To create the necessary overlap between layers, points are generated using a 4n+1 pattern along each isocurve domain, where n represents the minimum number of timbers in any given pair of layers. The point layers are flattened and divided into pairs, with alternate lists omitted, then reassigned to the parent layer. By reintroducing any omitted isocurve endpoints, points are generated that, when paired, form lines overlapping with the layer below and alternating due to the 4n+1 point structure. These guiding lines are then used to create timbers represented as boxes based on parametrized specifications and the originating surface.

Each line is populated with four points, serving as the basis for dowel placement. For layers with n elements, the first and last timbers have their two innermost points removed, enabling a direct connection between layers. Points are connected between layers on a point-by-point basis, with even-numbered points linking to the layer above and odd-numbered points linking to the layer below. This systematic assignment ensures that even-valued points connect to the subsequent layer while odd-valued points link to the previous one, establishing a stable dowel connection between all layers.

For circular or periodic structures, where isocurves are continuous and lack defined endpoints, a different approach is required due to the uniformity of n parameters between layers. In the prototype presented here, called the “basket” system, 4n points are generated as before, but every other layer is shifted by 1/2n units along the isocurve’s domain to achieve the necessary overlap. Following this workflow, two primary orientations—horizontal and vertical —are explored to meet the project’s design goals. One approach uses two single surfaces as guiding geometry, while another employs a circular form to establish a larger structure with a horizontal arrangement. Additionally, hybrid solutions were developed by combining both vertical and horizontal systems (Figure 2).

Performance and Analysis

In this phase, human agency—particularly from non-expert participants—is emphasized in shaping the algorithmic framework, which is tailored to site-specific factors such as solar exposure, wind patterns, and structural stability. Using computational tools, expert designers optimize the timber dowel structure, while non-experts provide input to refine design scenarios based on aesthetic, functional, and community-driven preferences. This approach promotes inclusivity by encouraging local stakeholders to engage in the design process, fostering a sense of ownership and empowerment within the community[22]. Engaging communities in design and construction processes is essential for addressing broader issues such as food security, environmental justice, the development of micro-community networks, and urban resilience[23, 24].

Feedback from prototyping and community involvement guided refinements to the computational framework. Additionally, a parametric model capable of adapting to both environmental and structural requirements is developed, drawing on principles of a Multi-Objective Optimization (MOO) framework as explored

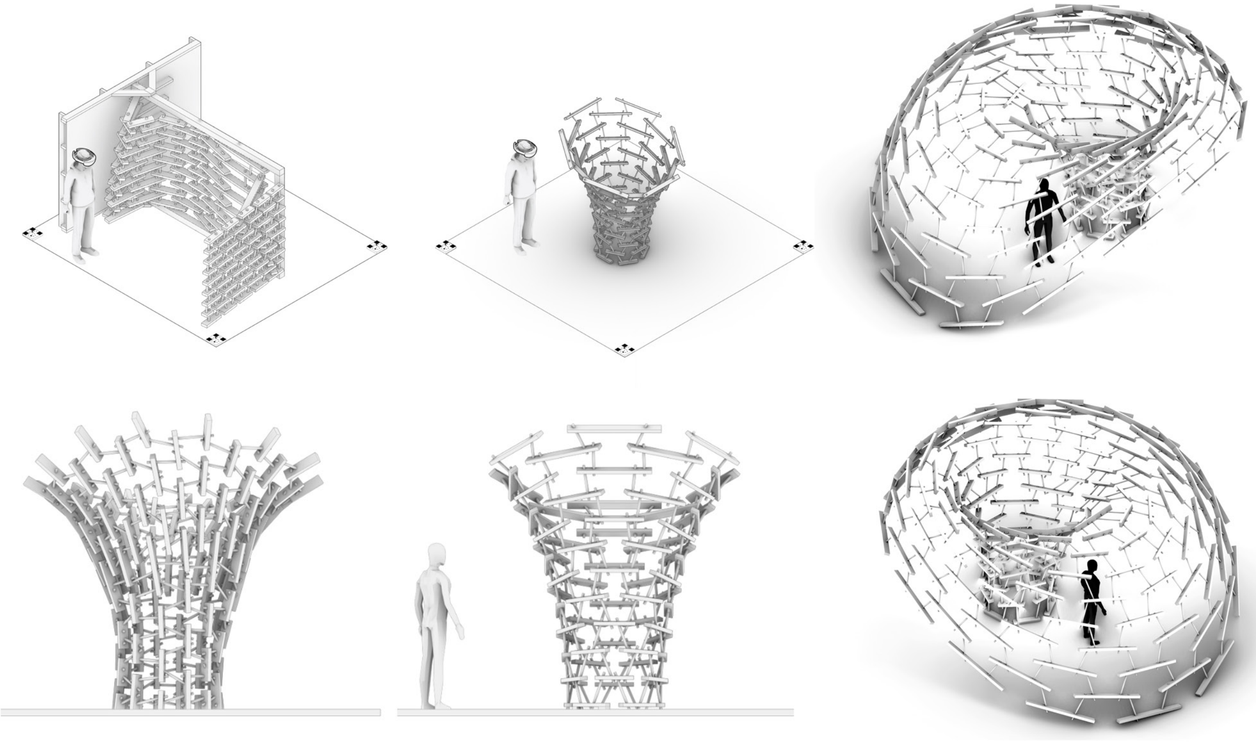

Figure 2. AR assembly models of the vertical and horizontal prototypes, utilizing QR codes

in literature and precedent projects[25]. Key parameters, including timber orientation, material allocation, and site-specific customization, were optimized to ensure the design meets both structural integrity and the preferences of the local community. These refinements enable the framework to support the development of multifunctional spaces that incorporate landscape elements, such as benches and canopies, enhancing both the usability and social function of the structure[26].

The parametric model facilitates performance analysis based on design parameters. This analysis includes material properties, such as structural integrity and resource efficiency, alongside context-aware factors like shading and solar gain. These assessments provide either one-time feedback for refining the design or can be incorporated into a multi-objective optimization process, which can be further explored in future studies.

Human Machine Co-Production

The integration of AR technology in the design-to-production process has proven transformative in community-driven projects by enabling collaborative construction and promoting capacity building. Research suggests that active participation in creating communal infrastructure strengthens social cohesion and provides opportunities for skill development among residents[27]. By offering real-time visualization and assembly assistance, AR empowers non-experts to contribute meaningfully to the project, democratizing the construction process and enhancing community resilience. This inclusive approach fosters shared responsibility in developing local infrastructure. Involving the community in the process addresses immediate access needs while building sustainable systems capable of adapting to future challenges, ensuring long-term stewardship of community resources [28].

The production workflow consists of three interconnected subsystems: AR-enabled cutting, robotic milling, and AR-guided assembly. Each subsystem's output feeds into the next process, with continuous feedback loops refining each stage. This iterative approach ensures that the production space informs the design space, integrating both constraints and opportunities specific to each production step. A schematic overview of this system is provided in Figure 3. In this phase, AR enhances collaboration between human operators and robotic systems throughout the cutting, milling, and assembly processes. Timber elements are tagged with unique QR codes containing their specific dimensions and assembly details, which serve as digital anchors to streamline the production process and minimize errors in material handling. Once milled, the timbers are stacked in preparation for assembly, where AR-enabled headsets allow users to interact with a shared extended reality platform. This platform supports effective collaboration by enabling users to select timber elements based on optimal strategies visualized in AR.

During the assembly process, humans using AR-enabled headsets collaborate with cobots through a shared extended reality platform. This platform visualizes optimal assembly strategies, allowing human operators to select timber elements and communicate commands via hand gestures recognized by the AR headset. The production workflow consists of three subsystems: AR-enabled cutting, robotic milling, and AR-guided assembly. Each subsystem's output feeds into the next, creating an iterative process where feedback refines each stage, ensuring that the production process actively informs the design. A schematic overview is provided in Figure 1, with further details in Figure 3.

The integration of human and machine agency enhances both precision and efficiency while establishing a foundation for community involvement. Timbers and dowels are organized into a descriptive typology, with each piece tagged based on its unique length, location, and orientation. The AR system utilizes these tags to assist in accurately positioning and orienting timbers during assembly. This collaborative framework supports adaptable design and augmented production, fostering an organized and participatory environment for community-driven construction.

AR-Enabled Cutting

As each timber has a unique length, an AR-assisted cutting process is used to display specifications for each element, utilizing a sliding miter saw equipped with two QR codes. This setup phygitally maps the target timber or dowel from the digital model directly onto the physical space, right in front of the person performing the cut (Figure 3). This approach eliminates the need for manual measurement of elements with varying sizes. The cutting setup is modeled in Rhino3D, with an anchor point positioned near the miter saw's centerline. As the user selects each element, it appears at this anchor point, based on its box coordinates. This allows the user to align and position the element, providing an additional layer of calibration for precise cutting.

After cutting, each timber is tagged along its edge. The preparation of these wooden elements involves using both a miter saw and an AR headset simultaneously. This combination allows the user to bypass the need for pre-measuring each piece, making the process more interactive and efficient, especially for large-scale production. Cutting hundreds of elements for each of the two prototyped projects takes approximately one hour, with one person operating the HoloLens headset and another assisting as needed for material handling or recalibrating the digital model to the headset. This collaborative approach streamlines the workflow, enabling quicker production times.

Robotic Milling

For milling dowel holes in the timber, a KUKA KR120 robotic arm equipped with a milling head is used, with timbers secured in place on a tray. The intersecting points of dowel lines with the timbers are grouped and organized, and normal vectors guide the milling head's orientation. Toolpaths, modeled in Rhino3D, allow for varying radii as needed. Robotic milling is chosen for its efficiency, with holes sorted in four orientations to optimize the robot's movement. A placeholder tray holds nine timber parts of varying lengths, and a buffer ensures smoother assembly. Using a six-millimeter spindle, the process of milling one hundred elements, each with an average of four holes, takes approximately thirty hours, including setup, demounting, and reloading. Figure 3 illustrates the pile of cut material resulting from the AR-enabled cutting, creating a pile of milled timbers with placeholder holes with one-inch diameters in multiple directions. The bottom right portion of Figure 3 shows the parametric simulation of the connected 3D model into robotic toolpath simulation.

AR-Enabled Assembly

The augmented assembly interface allows users to view specific elements or layers based on their location, with preceding elements visible as wireframes for clarity. Each element is tagged with text dots, and dowels are displayed only when they connect the current element to the previous one, with their length indicated. The Fologram application, installed on both the AR headset and Rhino Grasshopper, transfers model data, enabling users to control visual properties and assembly details. Users can customize their view by choosing to display dowels or adjust other visual elements, guiding the assembly of the timber dowel system. This interface helps users understand which dowels to add at each layer for seamless integration, while also allowing them to manage the level of detail and pace of assembly through the menu bars on the phygital interface.

Details such as timber layers and tags, dowel lengths, and roof and wall components are all accessible, with the option to view the complete structure. This approach empowers users to independently assemble the structure without needing to interpret technical drawings, relying instead on augmented guides throughout the process. The assembly difficulty varies depending on the vertical or horizontal orientation of the timbers and the dowel angles; more angled dowels provide better stability but can complicate assembly by pushing timbers in opposing directions. Figures 3 and 4 illustrate a user positioning timbers with an AR headset, alongside the two tested orientations—vertical and horizontal. For ease, both systems are assembled horizontally.

Material Passport

This phase focuses on material resourcing and the creation of a material passport directory, with two primary objectives: material allocation and resource repurposing. The directory of available materials is fed forward into the performance and analysis phase, where material choices are evaluated based on structural performance. Simultaneously, a waste material passport directory is established, feeding back into the design and parametrization phase to support resource-driven decisions.

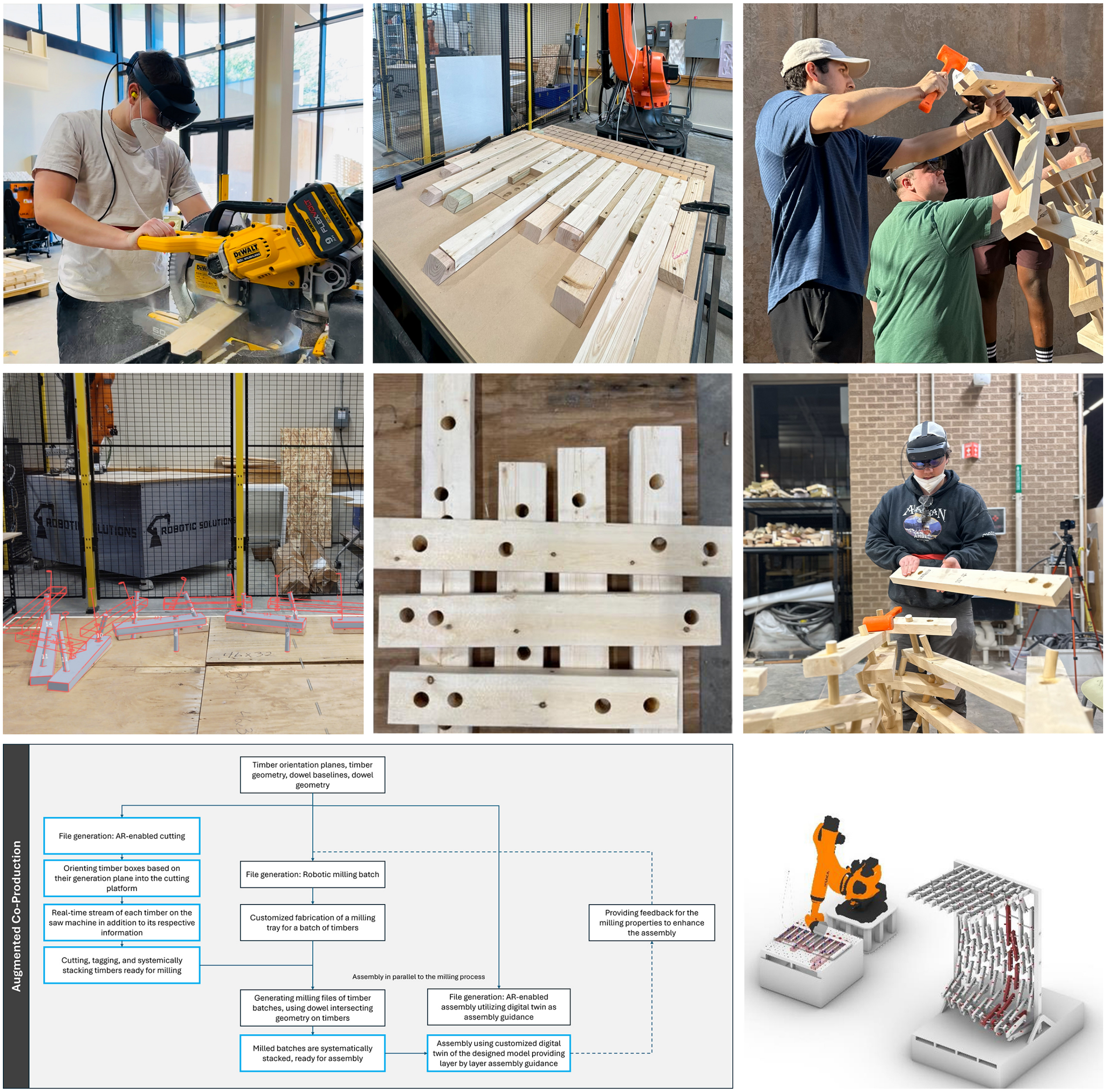

Figure 3. Top Two Left: First Instance Human Agency in AR enabled Cutting From raw material to customized elements. Top Two Middle: Robotic modification of timbers, preparing the timbers for the dowel assembly. Top Two Right: AR-enabled co-assembly of the timber dowel systems; both systems were assembled horizontally. Bottom Two: Overview of the Human Machine Co-Production workflow and respecting figure.

The resource repurposing process serves as both feedback and feedforward, documenting waste materials, including dowels and timber profiles. By creating a digital record, this phase enables the reintegration of waste materials into the design, providing input for resource-based complementary supports within the structure. This circular approach minimizes overall waste, a critical factor given the limited resources typical of community-led projects.

The project uses 2”x4” and 2”x6” timber beams, each 6’0” in length. As beams are cut to varied lengths, offcuts, referred to as “knots,” are generated. For each design parameter, a specific waste material passport is created, supporting targeted complementary designs. This passport provides insights into potential waste and informs the performance phase, as outlined in Section 3.2, enabling a circular design approach that aligns with sustainable material use and waste reduction.

Figure 4. Assembled Prototypes. Vertical System on the left and horizontal on the right.

Additionally, for dowels, the system allows for the allocation of various dowel thicknesses, including 0.5, 3/4, and 1 inch. The design is customizable according to the available sets of locally sourced materials, allowing for adaptable and resource-driven design decisions that optimize material use.

RESULT AND FUTURE WORK

This research demonstrates the integration of computational design, robotic fabrication, and AR-assisted cutting and assembly in constructing timber dowel structures through one-to-one prototyping. Two prototypes, showcased at a public event, First Friday Art Trails (Figure 5), allowed community members to engage with the structures and the AR interface. Feedback from the design, production, and demonstration phases has been informative and will guide the next phase of the project. The vertical timber structures, designed as walls with integrated benches, offer modular expansion and reconfiguration, while the horizontal system forms a central focal point with concentric circles, creating adaptable gathering spaces and expansive overhead structures.

The integration of computational design, robotic fabrication, and AR-enabled assembly has advanced the construction of timber dowel structures by providing customizable, efficient solutions tailored to site conditions and user needs. AR-assisted processes offer real-time visual instructions, making assembly intuitive even for those with minimal expertise, while robotic milling ensures precision. This project lays the groundwork for engaging community members in co-production, demonstrating the potential for collaborative construction. Future research will focus on developing more autonomous human-robot systems, incorporating advanced sensing technologies and digital twins for seamless human-robot interaction, including a collaborative assembly with cobots.

Future exploration focuses on expanding the optimization process to include additional environmental and social factors, enabling designs to adapt to changing site conditions through real-time data. Future work will also prioritize the systematic integration of resource-driven design principles—specifically, variations in dowels and timbers as well as a zero-waste material strategy—to enhance and evaluate the circularity aspects of the research, as these principles have been established and tested within the existing body of literature [29, 30]. In the production phase, AR has proven effective in guiding non-experts through tasks like cutting and assembly. Future improvements could involve more intuitive interfaces, such as voice commands or gesture controls, making AR easier to use across different construction environments and materials. Enhancing human-robot interaction by making robots more responsive to real-time input could give non-experts greater control over milling and assembly tasks.

ACKNOWLEDGEMENT

This research has greatly benefited from the dedication and support of the faculty, researchers, staff, and students at TTU HCoA and the Hi-DARS lab team. The design-to-production and analysis methods were initially developed by members of the Hi-DARS lab team at TTU HCoA and further explored and tested by graduate students as part of the Spring 2024 ARCH

Figure 5. Showcasing the prototype and in a local public event.

5334 course, Advanced Architectural Technology I, instructed by Sina Mostafavi. The prototype Bench was designed and realized by the team: Alexander Garza, David Nelson, Chance Welles, and Jakob Wiesner, with assistance from Research and Teaching Assistants: Cole Howell (RA), Brodey Myers (TA), Edgar Montejano (RA), and Bahar Bagheri (GRA). The core computational and augmented fabrication methods presented in this research were developed collaboratively by Bahar Bagheri, Sina Mostafavi, Edgar Montejano, and Cole Howell, each contributing to different aspects of the system. Additionally, Asma Mehan conducted a parallel joint seminar on Community Design Development at TTU HCoA ARCH 5384, which conceptually and theoretically contributed to the framework of the presented project. External collaborators, including members of the South Plains Food Bank, provided additional input and support. The authors express their sincere gratitude to all contributors.

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