Integrated Computational Design to Augmented Production of Timber-Dowel Structures

A multi-criteria system for informed variation and community co-production

Sina Mostafavi[1], Bahar Bagheri[2], Caleb Scott[3],
Edgar Montejano Hernandez[4], Cole Howell[5], Asma Mehan[6]
[1,2,3,4,5] Texas Tech University, Huckabee College of Architecture, Hi-DARS lab.
[6] Texas Tech University, Huckabee College of Architecture, AHU lab.
[1]sina.mostafavi@ttu.edu, ORCID: 0000-0002-7558-7569
[2]bahar.bagheri@ttu.edu, ORCID: 0009-0005-4400-418X
[3]caleb.r.scott@ttu.edu, ORCID: 0009-0009-5556-8764
[4]edgar.h.montejano@ttu.edu, ORCID: 0009-0004-9357-072X
[5]cole.dh@outlook.com, ORCID: 0009-0009-4383-974X
[6]asma.mehan@ttu.edu, ORCID: 0000-0002-7381-6663

Abstract. This research explores the design-to-production computational framework of a Timber Dowel System, emphasizing an integrated computational workflow informed by fabrication and assembly feedback. This workflow incorporates contextual and fabricability parameters, enabling a parametric framework optimized for performance, adaptability, and scalability. The initial design process utilized a modular plug-and-play approach, employing manually controlled surfaces and poly-surfaces to explore flexible geometries and structural configurations. Two full-scale prototypes were developed using AR-guided assembly and robotic milling, addressing production challenges such as dowel placement precision, material limitations, and assembly feasibility. Feedback from these prototypes informed refinements in the computational framework, translating into practical parameters to improve structural integrity and procedural efficiency. A horizontal orientation was prioritized due to its standalone stability, while multiple extensions of the initial basket prototype were analysed to evaluate and study the system performance under varied geometric configurations. By integrating community-driven requirements and contextual considerations, this research lays the groundwork for a multi-criteria framework that supports informed design variation and facilitates collaborative co-production workflows.

Keywords. Timber-Dowel Structures, Augmented Fabrication, Adaptive Tessellation, Data-driven Design, Robotic Wood fabrication

ARCHITECTURAL INFORMATICS, Proceedings of the 30th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2025, Volume 2, 397-406. © 2025 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

1. Introduction

Timber-dowel systems remain an underexplored yet promising construction method in wood architecture, offering significant advantages in structural performance, sustainability, and automation. Unlike conventional systems, timber-dowel structures eliminate the need for additional joint connections, relying on interlocking dowels for efficient assembly. This system is particularly suited to contexts where wooden materials are abundant and valued for their structural and contextual benefits. Its seamless integration into design-to-production workflows positions timber-dowel construction as a viable solution for innovative, high-performance architecture.

This research develops a computational framework for timber-dowel structures, emphasizing a fully parametric model that incorporates contextual and fabrication parameters. By integrating feedback from fabrication and assembly stages, the framework adapts to practical constraints and material properties, ensuring scalability and flexibility for diverse applications. This foundation supports future integration of multi-objective optimization (MOO) and multi-criteria decision-making (MCDM) systems to address structural and contextual requirements.

The study originated in a graduate-level course at Huckabee College of Architecture (HCoA) at Texas Tech University (TTU) in collaboration with South Plains Food Bank (SPFB), a humanitarian group supporting food-insecure communities in West Texas. Responding to the organization's need for a multifunctional gathering space, this project focuses on designing and prototyping a timber-dowel canopy. The canopy provides shelter while fostering community engagement through co-construction, participation, and learning. This research leverages computational design tools, AR-guided workflows, and robotic fabrication techniques to develop and assemble full-scale prototypes, integrating high- and low-tech methods to promote accessibility and collaboration.

This paper situates the study within advancements in timber-dowel systems and augmented production in architecture. The methods section details the computational framework, design typologies, and AR- and robot-enabled production workflows. Subsequent sections present the prototyping process, insights from fabrication feedback, and discussions on scalability and adaptability. The conclusion highlights the groundwork for implementing multi-objective optimization and scaling the system to larger, more asymmetrical forms.

2. Background

This research advances timber-dowel systems by integrating computational design, robotic fabrication, and augmented reality (AR) to streamline design and construction. Timber-dowel structures represent a sustainable and efficient alternative in wood construction, offering significant advantages in structural performance, cost efficiency, and automation. These systems eliminate the need for adhesives or metal fasteners by relying solely on interlocking dowels. The arrangement of timber and dowels has been explored in various configurations, including free-form shells, dowel-laminated slabs, and hybrid systems that integrate robotic fabrication processes (Thoma et al., 2019). Research has further advanced the field through computational methods such as genetic algorithms, which optimize dowel placement to reduce costs (Villar et al., 2016), and mixed-integer nonlinear programming, which enhances structural performance and material efficiency (Silih et al., 2010). Hybrid systems combining dowels with plates have also been developed to address specific structural challenges (Tang et al., 2020), and self-balancing capacities and assembly intelligence as demonstrated in the Timber-Dowel Reciprocal Lattice System (Mostafavi et al., 2024).

AR provides real-time guidance during cutting and assembly, offering detailed instructions and enabling precise alignments (Mann et al., 2015; Jahn et al., 2019). This has been applied in various areas, including timber construction (Jahn et al., 2022), bricklaying (Song et al., 2021), and formwork projects, where AR enhances accuracy and simplifies complex tasks. The research aims to combine advanced tools like AR and robotic milling with hands-on woodworking, creating a process that is accessible for non-experts (Mostafavi et al., 2024). The computational framework adapts to local conditions, such as available materials, generating flexible, parametric designs that can be easily adjusted. By replacing traditional technical drawings with interactive guidance, the system connects designers and builders through digital tools.

This approach promotes community participation by simplifying the construction process and making it inclusive (Mehan & Mostafavi, 2022). AR-guided cutting and assembly enable individuals with limited technical experience to contribute to urban structures, such as multifunctional gathering spaces. By blending digital and manual techniques, this research demonstrates how timber-dowel systems can deliver region specific solutions where wood is abundant and culturally significant.

3. Methods

This study builds on an integrated design-to-production workflow for timber-dowel systems, focusing on Design and Parametrization and Performance and Analysis, while outlining Human-Machine Co-Production and Material Passport (Figure 1). The Design and Parametrization phase establishes a computational framework that translates contextual, structural, and fabrication constraints into parametric designs. This enables glue-free, disassemblable timber-dowel structures tailored to community needs, using adaptive tessellation and parameters like timber orientation and dowel placement. The Performance and Analysis phase evaluates designs for structural integrity and contextual performance, addressing factors like solar shading, wind loads, and material efficiency, while incorporating community feedback to refine scenarios.

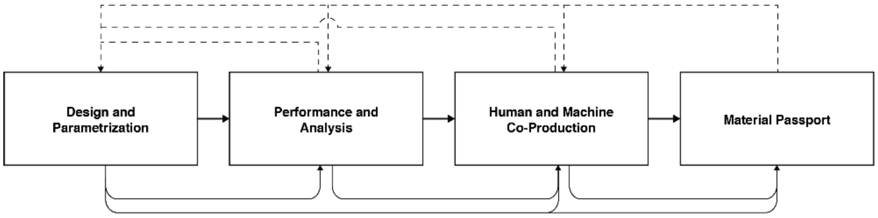

Figure 1. The overview of the design-to-production workflow and their interrelations

While the primary focus is on these two phases, the methodology also incorporates Human-Machine Co-Production, where AR and robotic fabrication streamline cutting, milling, and assembly processes, ensuring accessibility for non-experts. Additionally, the Material Passport phase tracks resource allocation and repurposes offcuts into future designs, promoting sustainable material use. Together, these phases create a collaborative, scalable workflow for developing resilient timber-dowel structures that integrate advanced computational tools with community-driven participation.

This research develops a computational framework and fully parametric model for timber-dowel construction, emphasizing the integration of contextual parameters and fabrication constraints. Timber-dowel systems are particularly suited to contexts where wood is abundant and culturally significant, offering structural performance without adhesives or joint connections. The production phase translates computational parameters into practical assembly methods, incorporating feedback to ensure a seamless design-to-production workflow. Augmented reality (AR) and robotic milling streamline cutting and assembly processes, enabling precise dowel placement and visual guidance for efficient construction. By combining advanced tools with hands-on woodworking, the workflow fosters community engagement while maintaining the structural and aesthetic integrity of the timber-dowel system.

To achieve this integrated workflow, a plug-and-play approach was first implemented using manually controlled surfaces. This system was prototyped as part of a graduate-level course, employing robotic milling, AR-guided assembly, and AR-enabled cutting to enhance co-production. These methods allowed community members to participate with minimal technical expertise, validating the system's potential during First Friday Art Trails (FFAT) public event in Lubbock, Texas. The production workflow demonstrated its efficiency, sustainability, and ability to engage the community, laying the foundation for broader applications.

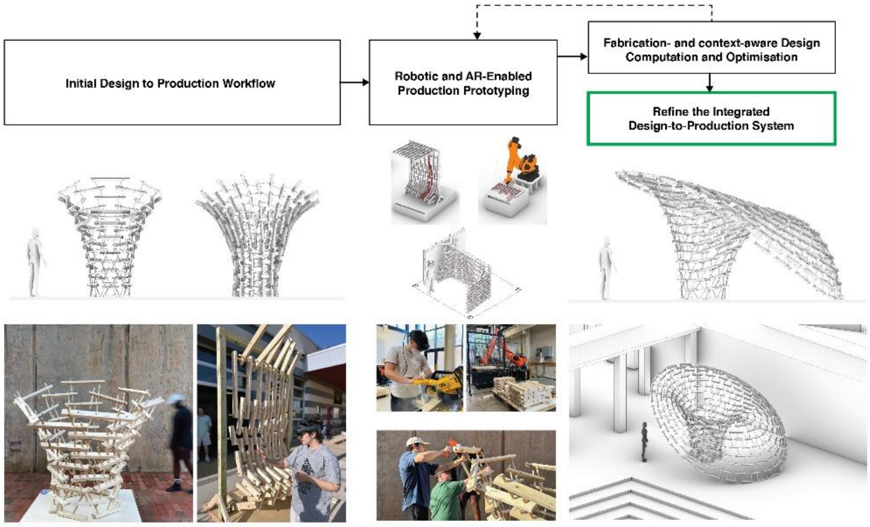

Figure 2. Overview of the methodology for design parameterization and performance analysis. Left: Horizontal and vertical design prototypes. Middle: Workflow with AR cutting, robotic milling, and

assembly. Right: Free-form scalable design shaped by structural and contextual factors.

In the next phase, fabrication challenges were incorporated into the computational framework. Feedback from the production process identified critical parameters, including optimal distances between layers, acceptable dowel angle ranges, and the benefits of horizontal assembly for standalone stability. These insights evolved the framework from a semi-parametric to a fully parametric model, integrating structural integrity analysis with fabrication considerations. This restructuring establishes the foundation for future research in multi-objective optimization, enabling the timber-dowel system to address contextual and structural performance while improving scalability and adaptability (Figure 2).

The proposed method operates through two integrated workflows. The design and computation workflow identifies and incorporates key parameters for structural performance and the geometrical properties of the system. The production workflow encompasses AR-enabled cutting, robotic milling, and AR-guided assembly.

3.1. PRODUCTION WORKFLOW

During the cutting phase, an AR headset displays specifications, streamlining the process with a sliding miter-saw and eliminating the need for manual measurements using digital twins of building components. Robotic milling, executed by a KR120 robotic arm, creates holes based on toolpaths derived from dowel line intersections.

During assembly, AR technology enhances precision by displaying wireframe guides and text tags for specific elements and layers. The Fologram plugin links Rhino models to a Hololens, streaming data to guide users through assembly without interpreting technical drawings. This system supports both vertical and horizontal timber dowel assemblies, adjusting for dowel lengths, angles, and timber positioning. Full-scale prototypes of each arrangement provide feedback for refining robotic processing and improving the assembly process.

3.2. DESIGN & COMPUTATIONAL FRAMEWORK

The computational framework uses surfaces and poly-surfaces as input geometry, incorporating adaptive tessellation to ensure structural integrity and contextual responsiveness. The workflow integrates parametric modelling tools, including Rhinoceros, Grasshopper, Python scripting, and robotic fabrication simulations. This approach enables adaptive design-to-production processes customized for the system.

3.2.1. Tessellation

The tessellation process begins with a guiding surface, where U-curves define timber orientations, and V-curves determine the number of timber rows and dowel directions. Based on prototype testing, timber layer spacing between 10 inches (0.253 m) and 30 inches (0.762 m) ensures structural integrity while providing adequate hand space during assembly. Smaller spacing improves convenience but limits shading potential, whereas larger spacing enhances shading at the expense of assembly ease.

The U-curves, subdivided from V-curves, guide timber placement layer by layer. Allocation depends on 1) alignment with the previous layer to ensure overlap across gaps and 2) variations in the number of timbers between layers. A fractal pattern is used, starting with n timbers in the base layer and progressively increasing by factors of n∗k and n∗k∗j to create systematic layer distribution (Figure 2). Points along U-curves define timber lengths, which are controlled globally to balance shading and structural performance. Longer timbers improve shading and integration but introduce higher buckling moments, requiring careful parameter control.

Feedback from robotic milling and assembly prototypes revealed a minimum offset of 2.5 inches (0.064 m) between dowel holes and timber endpoints, as well as between adjacent dowels, to reduce errors and enhance functionality. The system uses a weaving strategy, connecting each timber to at least two others in adjacent layers, with four dowels per timber ensuring stability. For layers with more timbers, the maximum allowable length in the less divided row supports a 2(k+1) configuration (Figure 3).

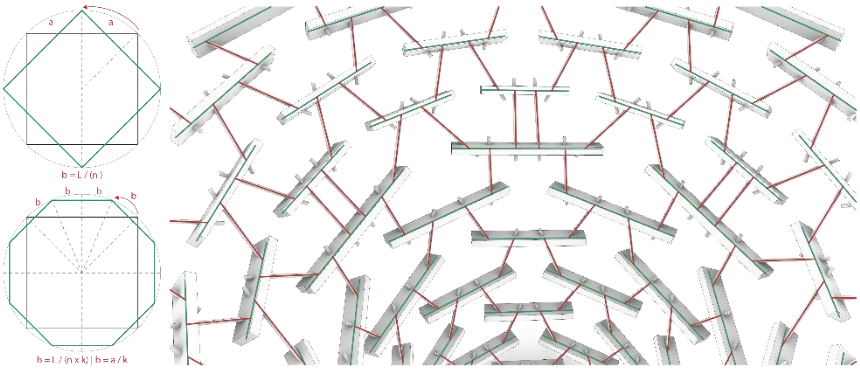

Figure 3. Left: Schematic representation of the variation in the number of timber elements across layers. Right: Close-up view of a segment of the timber dowel system.

Dowels are parametrically distributed along curves, based on incoming and outgoing coordinates. Points are tracked through a key system to generate curves, enabling organized dowel placement. Similar to timber lengths, dowel placement patterns are globally managed to reduce computational costs.

3.2.2. Structural Analysis

In this study, the Karamba3D plugin is used for its integration within parametric workflows and its capacity for structural analysis and profile optimization. Both timbers and dowels are modeled as linear elements with variable profiles. To enhance analysis accuracy, timbers and dowels are segmented at their intersections and treated as individual beam elements with consistent grouping IDs. This method prevents rigid body behavior and ensures realistic stress and displacement calculations. No joints are defined at the intersections since the system does not incorporate hinges. Supports are placed at ground connection points, located at the midpoints between dowel intersections.

The analysis evaluates two timber profiles—2" × 4" (50.8 mm × 101.6 mm) and 2" × 6" (50.8 mm × 152.4 mm)—alongside dowel diameters of 3/4" (19.05 mm) and 1"

(25.4 mm). Structural analysis is designed to asses three load cases: regional maximum wind loads based on EPW file data, self-weight of the structure, and an additional live load aligned with its intended use. These evaluations, illustrated in Figure 3.

4. Result

The structural performance of three distinct timber-dowel configurations—simple umbrella shape, dome, and one-axial symmetrical form—was analyzed using the Karamba3D plugin under gravity load conditions. For all configurations, timber beams were modeled with profiles of 2" × 4" (50.8 mm × 101.6 mm) and 2" × 6" (50.8 mm × 152.4 mm), while dowels had diameters of 3/4" (19.05 mm) and 1" (25.4 mm). Supports were appropriately positioned to facilitate accurate load transfer.

The simple umbrella shape exhibited maximum displacements of 1.49 cm near the upper edges, with stress concentrated in lower regions (-0.832 kN/cm²) and tensile stress peaking at 0.766 kN/cm² at the upper areas. Utilization peaked at 58.9%, highlighting the system's material efficiency and stability. The dome configuration demonstrated maximum displacement of 1.01 cm at the apex, with balanced stress distribution (-0.492 kN/cm² compressive and 0.466 kN/cm² tensile). Its peak utilization of 35.9% suggested ample room for material optimization. Conversely, the one-axial symmetrical form revealed significant vulnerabilities, with maximum displacements of 7.24 cm near its cantilevered edge and compressive stress up to -2.59 kN/cm² concentrated at the base. Utilization exceeded 100% in critical areas, indicating overstressed regions and the need for reinforcement. While each structure displayed its own strengths, the analyses identified opportunities for refinement and optimization tailored to their specific geometric and loading characteristics (Figure 4).

The structural performance of the three configurations highlights distinct differences in geometry, load distribution, and material usage. The simple umbrella shape demonstrates balanced material efficiency and stability, with moderate stress and displacement values, and a peak utilization of 58.9%. This configuration effectively uses material but offers limited potential for further optimization. The dome configuration shows the lowest displacement (1.01 cm) and well-distributed stress, owing to its symmetrical load distribution. With a peak utilization of 35.9%, the dome provides opportunities for material optimization, particularly at its base and apex. In contrast, the one-axial symmetrical form encounters structural challenges, including high displacements (7.24 cm) and stress concentrations that lead to over-utilization in critical areas. While innovative, this form demands reinforcement or design adjustments to improve load distribution. Overall, the dome exhibits the most stability and material efficiency, the umbrella shape delivers balanced performance, and the one-axial form requires refinement to address structural deficiencies. This analysis emphasizes the potential for genetic optimization tools to enhance structural performance and enable exploration of geometric variations.

The structural integrity of the timber-dowel system relies on balancing compressive and tensile forces within each configuration. The dome form, with its symmetrical geometry, excels in load distribution and stability, requiring minimal reinforcement. Conversely, the one-axial symmetrical form underscores the structural challenges posed by asymmetry, where uneven load distribution results in significant displacements and stress concentrations.

Figure 4. Structural analysis of three configurations: simple umbrella (left column), dome (middle column), and one-axial symmetrical form (right column). Top: Displacement, Bottom: Utilization.

Designing for both assembly and disassembly enhances sustainability and adaptability within the timber-dowel system. The use of counterbalanced forces supports glue-free construction, allowing for efficient assembly and reuse potential. The dome and umbrella configurations are easier to assemble due to their evenly distributed forces that work harmoniously with gravity to stabilize the structure. However, the one-axial symmetrical form presents assembly challenges, as uneven force distribution requires additional counterbalancing.

5. Conclusion

This research builds on the integration of computational design, robotic fabrication, and AR-assisted cutting to construct timber-dowel structures through one-to-one prototyping, offering critical feedback for refining final designs. By combining these technologies, a design-to-production system was established that actively engaged community members in the construction process while laying the foundation for multi-objective optimization and multi-criteria decision-making. Two full-scale prototypes were exhibited at a public event, allowing attendees to interact with the structures and the AR interface. Feedback gathered from the design, production, and demonstration phases emphasized community-driven insights to refine both form and functionality.

Drawing on feedback from the FFAT local exhibition and earlier production phases, a hybrid structure was developed, combining a double-curvature arched surface with volumetric baskets and columns. During fabrication, AR-assisted cutting significantly reduced preparation time, robotic milling ensured precise dowel placement, and AR-informed assembly provided holographic instructions that enabled participants, regardless of technical expertise, to contribute effectively. This iterative process demonstrates how computationally driven designs can balance structural integrity, modular adaptability, and inclusive community engagement, establishing a scalable approach to timber-dowel construction.

6. Research Outlook

This study emphasizes the importance of fabrication- and assembly-aware design in advancing timber-dowel systems. Insights gained from AR-informed cutting, robotic milling, and AR-guided assembly were integrated into the computational framework, addressing practical production constraints. For example, minimum offsets between dowel holes and timber endpoints were incorporated to resolve assembly challenges observed during prototyping. Adaptive tessellation and layer-by-layer weaving strategies illustrate how computational designs can effectively respond to fabrication requirements, improving both feasibility and scalability. This process establishes a reliable workflow that balances structural performance, material efficiency, and production adaptability.

The inclusion of material passports supports a zero-waste, resource-conscious approach, documenting material specifications and offcuts to optimize resource use and repurpose surplus materials. This framework aligns with circular design principles, enabling leftover timber and dowels to be reused in complementary applications while reducing waste. Community engagement, facilitated by AR tools, highlights the potential to make construction processes more accessible by empowering participants to collaborate and contribute meaningfully to sustainable building practices.

Future work will focus on the large-scale fabrication of a one-to-one pavilion, co-developed with the target community, to validate the system's scalability and adaptability. This phase will explore structural reinforcement strategies, including reinforcing areas with major displacements and introducing adaptive informed variation based on performance requirements. This may require local parameterization, leveraging techniques such as agent-based modeling and machine learning applications to refine designs further. Additionally, mapping human agency will include investigating human-robot collaboration for assisted and augmented assembly and production, enhancing the co-production process and ensuring seamless interaction between digital tools and hands-on construction. These steps aim to further align the computational framework with functional and community-driven requirements in timber-dowel construction.

Acknowledgements

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 and further explored and tested by graduate students as part of the Spring 2024 ARCH 5334 course, Advanced Architectural Technology I, instructed by Sina Mostafavi. Two key projects form the foundation for exploration: Landscape + Canopy (Brandon Paleo, Garrett Whitehead, Gunner Murrell, Jack Dittrich, Jacklyn Hurtado, Jakelin Silva, Kathleen Gutierrez, Max Halwas) and Oven + Canopy (Aaron Malavolta, Amanda Gomez, Apollo Nyoma, Caleb Scott, Gabe Herrera, Harmony Smith, Mattia Hajmeli, Robin Mutchler), with assistance from Research and Teaching

Assistants: Cole Howell (RA), Brodey Myers (TA), Edgar Montejano (GRA), and Bahar Bagheri (GRA). The core computational and augmented fabrication methods presented in this research were further developed collaboratively by B. Bagheri, S. Mostafavi, E. Montejano, and C. Scott, each contributing to different aspects of the system. Additionally, Asma Mehan conducted a parallel joint seminar on Community Design and Development Resources (ARCH 5384) in Spring 2024 at TTU, which conceptually and contextually contributed to the framework of the presented project. External collaborators, including members of the SPFB, provided additional input and support.

References

Jahn, G., Newnham, C., & van den Berg, N. (2022). Augmented reality for construction from steam-bent timber. *CAADRIA Proceedings.* https://doi.org/10.52842/conf.caadria.2022.2.191

Jahn, G., Newnham, C., van den Berg, N., Iraheta, M., & Wells, J. (2019). Holographic construction. *Impact: Design With All Senses*, 314–324. Springer International Publishing. https://doi.org/10.1007/978-3-030-29829-6_25

Mann, Steve, Steve Feiner, Soren Harner, Mir Adnan Ali, Ryan Janzen, Jayse Hansen, & Stefano Baldassi. Wearable Computing, 3D Aug* Reality, Photographic/Videographic Gesture Sensing, and Veillance. *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, January 15, 2015. https://doi.org/10.1145/2677199.2683590.

Mehan, A., & Mostafavi, S. (2022). Building Resilient Communities Over Time. In: Brears, R.C. (eds), *The Palgrave Encyclopedia of Urban and Regional Futures*. Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-030-87745-3_322.

Mostafavi, S., Bagheri, B., Bao, D., W., & Mehan, A. (2024). 6.2. Smart Prototyping: From Data-Driven Mass-Customization to Community-Enabled Co-Production. In: Kanaani, M (Ed.), *The Routledge Companion to Smart Design Thinking in Architecture & Urbanism for a Sustainable, Living Planet*. Routledge. ISBN: 9781032469904.

Mostafavi, S., Ghiyasi, T., Montejano Hernandez, E., & Howell, C. (2024). Timber-Dowel Reciprocal Lattice System: Design Computation to Assembly, Case Study on Tetrahedral-Octahedral Voxelization. In *IASS 2024 Symposium: Redefining the Art of Structural Design*. Zurich, Switzerland.

Šilih, S., Kravanja, S., & Premrov, M. (2010). Shape and discrete sizing optimization of timber trusses by considering of joint flexibility. *Advances in Engineering Software, 41*(2), 286–294. https://doi.org/10.1016/j.advengsoft.2009.07.002

Song, Y., Koeck, R., & Luo, S. (2021). Review and analysis of Augmented Reality (AR) literature for digital fabrication in Architecture. *Automation in Construction, 128,* 103762. https://doi.org/10.1016/j.autcon.2021.103762

Tang, L., Yang, H., Crocetti, R., Liu, J., Shi, B., Gustafsson, P. J., & Liu, W. (2020). Experimental and numerical investigations on the hybrid dowel and bonding steel plate joints for timber structures. *Construction and Building Materials, 265*, 120847. https://doi.org/10.1016/j.conbuildmat.2020.120847

Thoma, A., Jenny, D., Helmreich, M., Gandia, A., Gramazio, F., & Kohler, M. (2019). Cooperative robotic fabrication of Timber Dowel Assemblies. *Research Culture in Architecture,* 77–88. https://doi.org/10.1515/9783035620238-008.

Villar, J. R., Vidal, P., Fernández, M. S., & Guaita, M. (2016). Genetic algorithm optimisation of heavy timber trusses with dowel joints according to eurocode 5. *Biosystems Engineering, 144,* 115–132. https://doi.org/10.1016/j.biosystemseng.2016.02.011.