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Timber-Dowel Reciprocal Lattice System: Design Computation to Assembly, Case Study on Tetrahedral-Octahedral Voxelization

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Abstract

This research introduces an integrated computational design-to-robotic production and augmented-reality-enabled assembly of reciprocal lattice structures using timber-dowel elements. The presented system, titled Timber-Dowel Reciprocal Lattice (TDRL), eliminates the need for connections with secondary materials such as metals or 3D-printed joints. The method employs robotic milling to produce timber elements with placeholders for dowels with varying profiles at specific spatial angles; these dowels are reciprocally displaced, generating counterbalancing forces that obviate the need for adhesive materials, as the vectors self-balance the assembly. The modular design allows it to function seamlessly across different scales and densities. Additionally, structurally informed variation of the dowels results in a resource-driven design workflow where sets of available materials can be chosen at the early stage of design. In the prototyped case study, a tetrahedral-octahedral honeycomb voxelization is selected as the space-filling discretization method with its rectangular base topology in horizontal sections and triangular facets in oblique directions. Eventually, the horizontal timber elements contribute to the structural integrity of the entire TDRL system by supporting the dowels through tension. The structure is assembled using AR-enabled workflows from the bottom layers to the top, and as the dowels reciprocate spatially, the opposing forces hold the timbers in their designated coordinates in space. This paper provides a research background and describes the voxelization and procedures, discusses parametric structural analysis and streamlines the workflow for resource-driven design, robotic production, and assembly of the developed TDRL structures.

Keywords: Timber-Dowel Structures, Reciprocal Lattice Structures, Robotic Wood Construction, AR-Assembly, Resource-Driven Design

1. Introduction

Lattice structures, characterized by their topological order and three-dimensional open-cell composition, consist of one or more repeating unit cells. Also recognized as 3D space frames, their lightweight nature and ease of assembly-disassembly have been acknowledged in several research and design projects. Recent advancements in digital design and fabrication, such as 3D printing and robotic production, have facilitated the construction of customized lattice structures with non-repetitive modules. Lattice structures are notable for their structural integrity and lightness, yet traditional assembly methods often rely on secondary materials for connections, which complicates both the assembly and disassembly processes. In this context, the integration of computational design and robotic fabrication with augmented reality (AR) assembly processes represents a transformative opportunity for the design and construction of timber structures. Advancing an alternative approach for the design and production of lattice systems, this research introduces the Timber-Dowel Reciprocal Lattice (TDRL) system. This method leverages the capabilities of robotic production and augmented reality (AR) for assembly, eliminating the need for secondary materials and connections in constructing lattice structures.

Voxelization is central to the TDRL system. In the presented case study, a tetrahedral-octahedral honeycomb voxelization is used for the arrangement of timber and dowel elements. Robotic milling allows for fabricating timber elements with placeholders that hold dowels at designated angles. Additionally, the dowels are displaced reciprocally. This reciprocalization generates counterbalancing forces that stabilize the assembly without the need for adhesive materials. The system's modularity facilitates adaptability across various scales and densities, while the selection of dowel profiles according to structural analysis enables a resource-driven design approach from the early stages of the design process. Moreover, the discrete nature of the developed system facilitates the integration of AR-enabled assembly workflows. This paper provides an overview of the developed methods with the main focus on the voxelization and reciprocalization procedures and outlines the workflow for resource-driven design, robotic production, and AR-enabled assembly of TDRL structures. This paper provides a research background and introduces the developed methods across three subsections: design computation, fabrication and assembly, and materials and structures. It concludes with a discussion of potential future work and further advancements of the system.

2. Background

Four key areas of prior research form the foundation of the developed system: Lattice Structures, Timber Dowel Structures, Reciprocal Structures, and Augmented Fabrication and Assembly. The developed and presented Timber-Dowel Reciprocal Lattice (TDRL) system draws on these four research areas to introduce an integrated design to production workflow for the assembly reciprocal lattice structure.

Lattice Structures: The study of lattice structures, defined by their polyhedral cellular composition of repeating units, has been extensively researched (Maconachie et al. [1]). Concurrent advancements in computational design tools have facilitated the development of customized, non-repetitive lattice modules and components (Naboni et al. [2], Kontiza et al. [3], Kladeftira et al. [4]). The presented method exploits the versatility of robotic fabrication, introducing a modular and resource-driven approach for designing and producing wooden lattice structures using tetrahedral-octahedral honeycomb tessellation.

Timber Dowel Systems: In wooden structural systems, the arrangement of timber and dowel elements has been examined across a range of configurations, from free-form shell structures fabricated with timber-dowel elements to dowel-laminated timbers used in slab constructions (Thoma et al. [5]). Related research includes optimizing timber structures through genetic algorithms (Villar et al. [6]), applying mixed-integer nonlinear programming (Šilih et al. [7] & [8]), and enhancing dowel connections with bonded steel plates (Tang et al. [9]). In the methodology presented in this paper, structural analysis informs the allocation of cross-sections for dowel elements to enhance structural efficiency and cost-effectiveness.

Reciprocal Structures: Numerous studies have focused on developing computational tools and methodologies tailored to the design and production of reciprocal frame (RF) structures. Pioneering work in this domain includes interactive computational frameworks for RF design, considering multiple criteria such as aesthetic, tessellation, and the optimization of rod alignments (Song et al. [10]). Researchers have proposed computational approaches to predict and govern the geometric configurations of intricate reciprocal element networks, addressing unique fabrication challenges (Parigi & Kirkegaard [11], Mostafavi et al. [12]). Tools used in 3D graphic statics and polyhedral reciprocal diagrams have emerged, enabling the creation and manipulation of complex, funicular, compression-only structural forms (Nejur & Akbarzadeh [13]).

Augmented Fabrication and Assembly: The convergence of robotic fabrication and advanced manufacturing techniques has shown significant potential in constructing timber structures. Computational strategies have been employed in projects like "Sequential Roof," involving the robotic assembly of massive freeform timber trusses, accompanied by the development of algorithms for nail connections and strategies to overcome fabrication constraints (Apolinarska et al. [14]). Research has investigated the application of robotic fabrication to upscale additive digital fabrication methods for industrial-scale timber assembly, optimizing structural design and efficiency (Willmann et al. [15]). Case studies have explored the robotic fabrication of nail-laminated timber structures, unveiling human-robot collaborative assembly processes (Ruan & Adel [16], Mostafavi et al. [17]). In the field of assembly design and evaluation for reciprocal architectural systems, computational methods have been proposed to integrate parametric assembly design with structural analysis and optimization (Torghabehi et al. [18]). Additionally, AR technologies have been employed to guide and evaluate assembly sequences, enhancing the capabilities of robotic production (Jahn et al. [19], Mitterberger et al. [20])

3. Methods

The primary focus of this research centers on the methods developed and prototypical material systems proposed, which encompass three main components. Each component consists of tailored contributions and research findings, detailed in the following sections: Design computation, fabrication and assembly, and material and structure. Figure 1 illustrates an overview of the integrated workflow.

3.1. Integrated Design Computation

The integrated workflow of the timber-dowel reciprocal lattice system is designed to accept any input surface or volumetric geometry. Initially, the system generates voxels; then, timber and dowels are sorted. In the subsequent reciprocalization phase, the dowels are shifted in opposing directions to create the reciprocal system. A detailed description of these two key phases, voxelization and the development of the reciprocal system, is provided below.

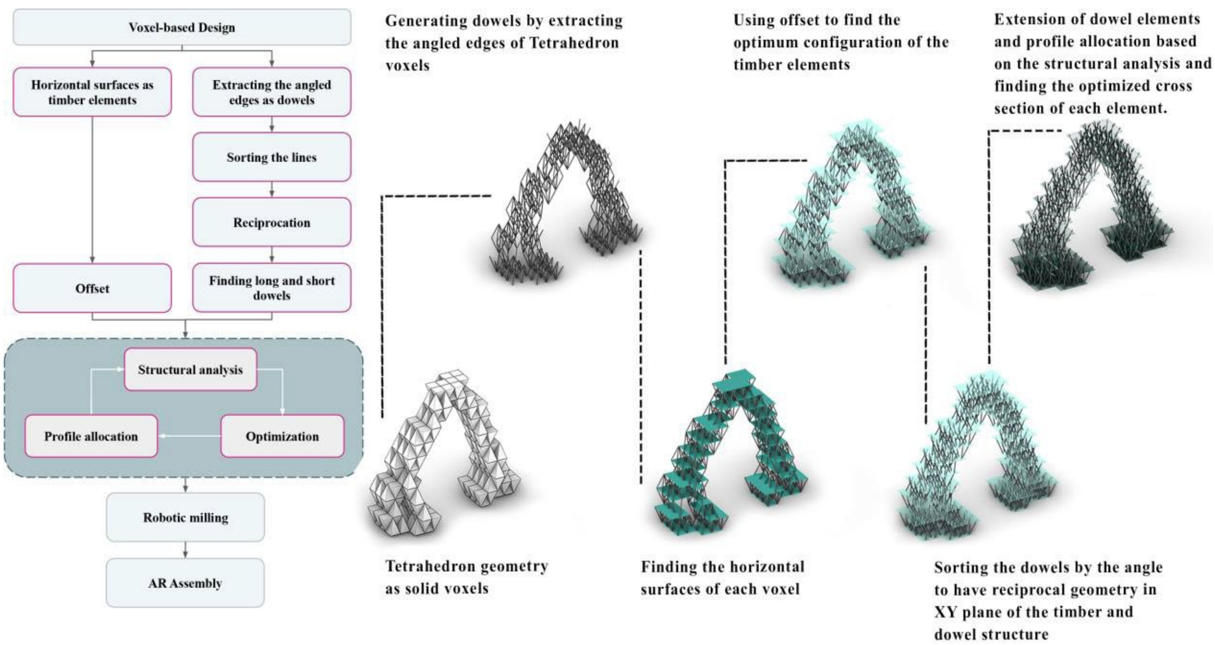

Figure 1. Left: An overview of integrated design, fabrication, and assembly workflow of Timber-Dowel Reciprocal Lattice system. Right: Applying the TDRL system to an arch case study illustrating voxelization to materialization phases

3.1.1. Voxelization and Aggregation

A voxel can be understood as the three-dimensional equivalent of a pixel in two-dimensional space, representing the smallest distinct unit of a 3D object or space in the context of octree representation (Foley et al. [21]). The present study harnesses the voxel-based design approach using tetrahedral-octahedral honeycomb geometry. This integration facilitates three-dimensional space-filling tessellation. The method empowers users to input freeform shapes or geometries, which are subsequently transformed into three-dimensional voxelated structures. This output, in turn, serves as an input for the reciprocation system, illustrating the versatility and applicability of the voxel-based and modular approach in design processes.

The starting point for the design can be a surface or volume to be voxelated. Alternatively, the designer can directly populate the space with the voxels by stacking the voxel modules next to each other, or the distribution of the voxels can be computed with methods such as topology optimization. Figure 2 shows the process of generating the initial voxel-based geometry, which will subsequently be transformed into the Timber-dowel reciprocal lattice structure.

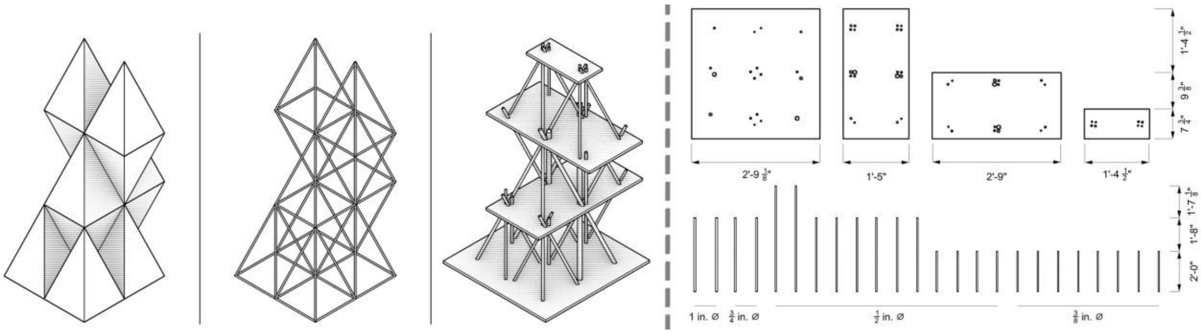

Figure 2. An overview of voxelization to materialization of TDRL system

3.1.2. Reciprocalization

The reciprocalization begins with the identification of sets of voxels, from which oblique elements are extracted and represented as lines, known as dowels. The remaining edges define rectangular profiles, which are joined as surfaces and labeled as timber elements. The reciprocalization process commences with these two sets of geometric data, including lines and surfaces. The steps to create a timber-dowel reciprocal lattice structure are as follows: The lines are grouped into four sets based on their spatial orientation. To each of these sets, horizontal displacements will be applied in opposing directions (-x, +x, -y, +y) to create a reciprocal system, which is illustrated in Figure 3. The displacement factor plays a crucial role in determining the extent of reciprocalization. The more elements are shifted in the x and y directions, the greater the offset in the vertices of the lines compared to their original positions on the vertices of the input voxels. Simultaneously, the horizontal elements are assembled into groups to form surfaces that represent timbers. As the lines undergo displacement for reciprocalization, an offset becomes necessary to accommodate all oblique elements or the dowels. This offset ensures that the dowels can penetrate the horizontal elements without encountering collisions. This procedure is illustrated in Figure 3, where the top shows the horizontal section of four modules, and the bottom layers show an isometric view of the prototyped system before and after reciprocalization.

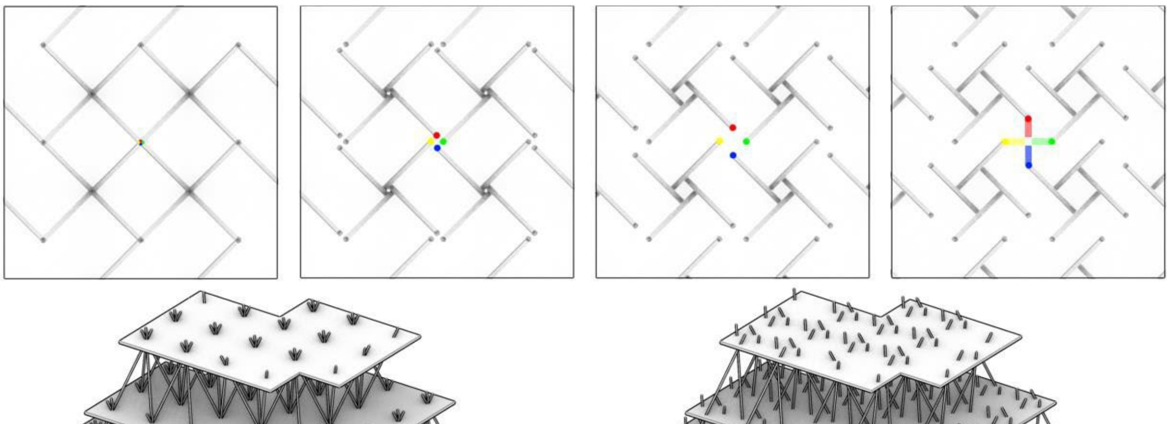

Figure 3.Top: Reciprocalization is shown on a horizontal profile of four voxels where the reciprocalization factor is increasing from left to right; Bottom: Isometric views of the prototyped system pre- and post-reciprocalization,

At this stage, there are elements that connect one or more levels together. Depending on the dowel lengths, it becomes feasible to filter out elements exceeding the available resource material and then divide them into smaller lengths. Subsequently, all lines in the subsystem are extended in both directions, ensuring they penetrate the top and bottom faces of the timber elements once they are placed. However, another constraint is set to avoid intersections with elements above or below themselves. Dowels are subsequently created along the lengths of each line, utilizing specified radii. The prototype showcased in Figures 1 and 3 incorporates a structural analysis routine based on which radius or dowel thickness to each line is assigned. Following this, the intersection between the dowels and timbers will be subtracted from the timbers by robotic milling, creating holes designed to hold the dowels at the designated angle. The horizontal timber elements enhance the system's structural integrity by supporting the dowels through tension, while the dowels, primarily under compression, transfer the load vertically from top to bottom. As the dowels reciprocate spatially, the opposing forces maintain the timbers in their designated spatial coordinates.

3.2. Fabrication and Assembly

The developed method utilizes robotic milling, incorporating multi-directional milling to remove the intersection between dowels and timbers, as shown in Figure 4. Dowels can be cut numerically using CNC machines, manual tools, or AR enabled cutting setups. The latest is used in the presented prototype. Assembly can be automated or assisted through augmented reality, with the choice dependent on the complexity and density of the structure. Additionally, given the modular structure, human-robot collaborative design and assembly workflows can be utilized (Mostafavi et al. [17]).

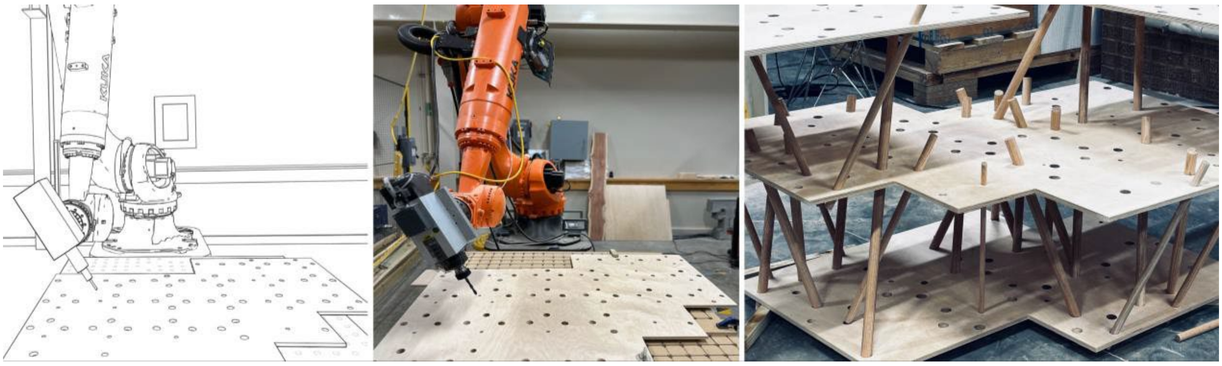

Figure 4. Robotic production and assembly. Left: A demonstration of the robotic production workflow, with the simulated phases on the left and the corresponding phases on the right. Right: Assembly and inserting dowels to the corresponding place.

3.2.1. Robotic Fabrication

Using robotic multi-directional milling, the process is programmable for different dimensions and configurations of voxels where milling angles are aligned with the angles of dowels. The left side of Figure 4 illustrates the simulation process of robotic production next to the production photo, where holes are applied from four different angles. The simulation is conducted using the KUKA|PRC add-on plugin within the Rhino-Grasshopper interface. This system is adaptable to work with a variety of dowel diameters. In the presented prototypes, the dowel diameters span from 3/8 inch to one inch. This variation requires an adjustment in the drilled hole diameters, a factor systematically addressed during the design phase, considering various parameters such as structural considerations and resource availability. This flexibility highlights the approach's adaptability and the system's focus on performative customization and circularity in construction. Consequently, the project employs a resource-driven design approach from the outset, mirroring practical adaptations to the availability of material sources. The fabrication process integrates a six-axis industrial robotic arm into the sequence, serving as a key component of the integrated design-to-production. The milling head is equipped with a 6 mm diameter drill bit. Oak wood is chosen for dowels, with 3/8-, 1/2-, 3/4-, and 1-inch diameters (9.5 to 25.4 mm).

3.2.2. Assembly and Sequencing

The developed fabrication and assembly process follows a series of steps. First, dowels are cut to predetermined lengths and radii, ensuring alignment with the structurally analyzed model. Timber elements are robotically milled to remove holes in varying angles and diameters to hold dowels. The assembly method adopts a systematic approach, commencing with the longest dowels that connect three or more horizontal timbers and progressing to the shortest, which only connect two layers of timbers. The placement of the first four opposing direction dowels stabilizes each timber layer, allowing subsequent dowels to fortify the overall structure. Dowel lengths are determined by structural requirements, each having a fabricated counterpart hole with an identical radius in the timber structure. Holes in the timber elements match corresponding dowels with different thicknesses.

In preparation for assembly, timbers are prioritized based on removal difficulty, with emphasis on those closest to the ground or support structures. Simultaneously, dowels are categorized by the last element they pierce and sorted into lists based on radius and length, providing guidance for the assembly process. In the presented prototypes, an augmented reality (AR) workflow is implemented to tag and organize layers of timbers and sets of dowels according to the assembly sequence. This enables the assembly team to interactively navigate through the list, revealing the position, orientation, and details of each element. This approach ensures a modular assembly process as shown on the right side of Figure 4.

3.3. Material and Structure

The TDRL system uses a resource- and data-driven design strategy for material allocation and eliminates the need for secondary materials in joints and connections through an integrated computational design approach. This is done by incorporating reciprocal geometry and structural optimization, which enhance structural performance by minimizing the mass and displacement at the same time. The key innovation lies in the jointless reciprocal lattice design, achieved through the integration of tetrahedral-octahedral geometry where each linear element moves at the same angle but in different vectors, creating a consistent geometry that avoids the complexities of typical space frame structure connections, as shown in Figure 5. Underpinning the structural system is a multi-objective optimization process, utilizing computational algorithms to evaluate load and support cases, material properties, and geometric configurations to achieve efficient material usage and load transfer, including distributed or point loads as needed in the design as well as the weight of the structure. This is further enhanced by dynamically allocating customized structural profiles within the lattice, optimizing each component based on the load each element receives. This approach marks an advancement in the materialization of lattice systems, opening new avenues for efficient and circular design and construction of wood structures.

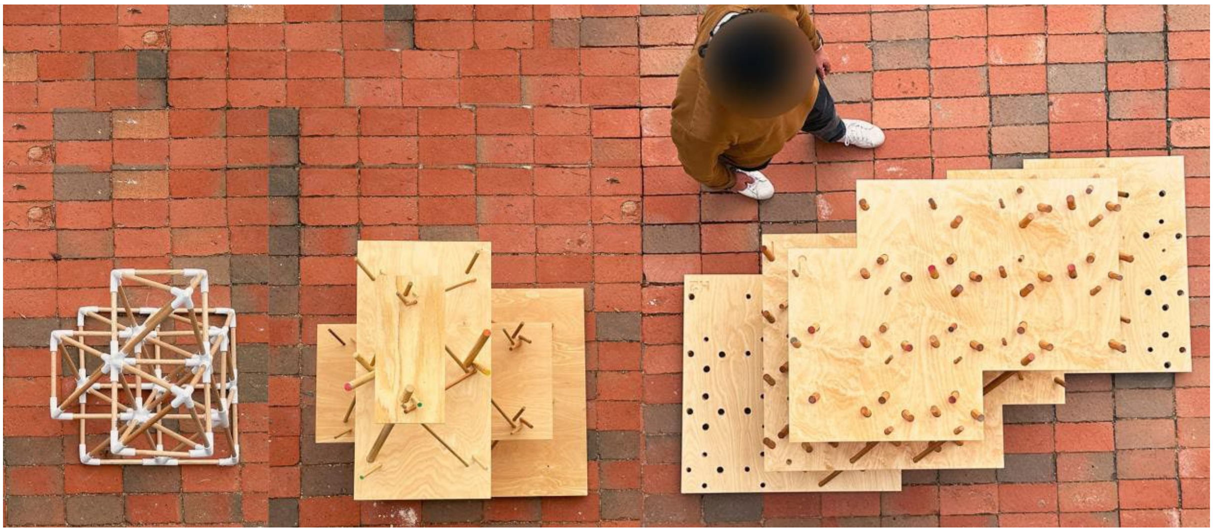

Figure 5.Top view of designed and assembled prototypes utilizing the Timber-Dowel Reciprocal Lattice (TDRL) system.

3.3.1. Structural Model: from a joint based to jointless lattice system

The utilization of an integrated design to production and the reciprocalization has resulted in a jointless lattice system. This tailored feature stems from the pursuit of a structural system which benefits from counter balancing force vectors of the voxels in opposing directions. The decision to eliminate conventional joints and structural connections marks a significant shift in design and construction of lattice structures.

Hence incorporating the reciprocal system through the whole timber and dowel structure allows for jointless fabrication and assembly. The essence of this reciprocal process is demonstrated by the uniform movement of all linear elements, with each one moving at the same angle but along different, orthogonal vectors. This consistent angular movement across various vectors is key to achieving a self-balancing reciprocal system. In the current case study, a tetrahedral-octahedral honeycomb voxelization with rectangular horizontal profiles is utilized, aligning the movement of the dowels with the x and y vectors. In scenarios involving different polyhedral topologies, a similar approach can be applied, provided the movements align with the directionalities of the base voxels.

3.3.2. Structural Optimization and Profile Allocation

In the Timber-Dowel Reciprocal Lattice System, the workflow employs advanced computational algorithms for optimization, focusing on the most efficient material usage and structural form utilization. This process involves iterative simulations to evaluate various load scenarios, material properties, and geometric configurations, aiming to balance structural stability with material usage. The optimization process enhances performance and supports circularity by minimizing waste and maximizing resource efficiency. A key aspect of this process is the dynamic allocation of profiles within the lattice, facilitated by the development of an integrated computational design workflow using Karamba3D as a structural analysis add-on plugin. This system assigns profiles with varying radii and lengths to elements based on structural analyses, leading to performative differentiation of structural elements where each component is tailored for its structural function. The profile allocation is dynamic, allowing adjustments in real-time during the design process, which provides significant flexibility and adaptability to meet varying project requirements, site conditions, and available material palettes.

3.3.3. Resource Driven Design and Circularity

Recent research and practical endeavors have highlighted the significance of circular design and construction within the AEC sectors (Çetin et al. [22], Heisel et al. [23]). Building on the principles of circular thinking, the TDRL System emphasizes a resource-driven design that prioritizes sustainable, renewable, and locally sourced materials to minimize environmental impact. Timber and dowels are specifically selected for their biodegradable and renewable properties, although the system's methodology could be applied to other material sets. Additionally, the system incorporates design for disassembly, enabling easy dismantling and facilitating the recycling or reuse of components. This enables easy disassembly and the recycling or reuse of components, supported by the fact that the developed method facilitates the design and assembly of jointless, glue-less, and modular structures. This approach promotes the reuse of components in various configurations or new projects, thereby extending material lifecycles and reducing waste.

4. Discussion and Conclusion

The Timber-Dowel Reciprocal Lattice (TDRL) system presented in this paper introduces a bespoke design to production workflow for resources driven discrete assembly of spatial structures. By developing integrated computational design methodologies, robotic fabrication, and augmented reality-enabled assembly workflows, this approach addresses several key challenges associated with state-of-the-art design, fabrication and assembly of lattice systems.

One of the central advantages of the TDRL system is its ability to eliminate the need for secondary materials or adhesives in the construction process. This is achieved through the purposeful use of reciprocally displaced timber dowels, which generate counterbalancing forces that stabilize the overall structure. The self-supporting nature of this system not only streamlines the construction process but also aligns with principles of sustainability and material efficiency, as it minimizes the embodied energy and waste associated with additional connectors or fasteners.

Moreover, the modular design of the TDRL system facilitates adaptability across different scales and densities, enabling its application in a wide range of architectural projects. The structurally informed variation of dowel profiles further enhances this flexibility, allowing for resource- and data-driven design workflows that optimize material usage based on structural requirements and material availability. This aspect of the system is particularly significant in the context of circular construction practices, as it promotes the efficient utilization of resources and minimizes waste.

The integration of robotic fabrication techniques into the TDRL system is crucial for ensuring precision during the production phase. Multi-directional robotic milling creates precise placeholders for dowels at calculated angles, enabling seamless assembly of the structure. Additionally, the implementation of augmented reality (AR) workflows enhances the assembly process by allowing for sequential assembly of the structure and facilitating human-robot collaboration. By providing interactive navigation and real-time visualization of element positions, orientations, and details, the AR-enabled approach streamlines construction and minimizes the potential for errors. This integration of emerging technologies showcases the possibilities for blending traditional construction techniques with advanced digital tools, paving the way for innovative building practices.

While the TDRL system offers numerous advantages, it's important to recognize the potential challenges and limitations. Successful implementation demands high levels of coordination and integration across the design, fabrication, and assembly stages. Moreover, the adoption of advanced technologies like robotic fabrication and augmented reality can introduce additional costs and require specialized expertise, which may limit broader adoption in some contexts. Despite these challenges, the timber-dowel reciprocal lattice system demonstrates the value of interdisciplinary collaboration and the integration of computational design, advanced fabrication techniques, and emerging technologies in structural design. By promoting resource-efficient building practices, this research contributes to the ongoing discussion on circular construction methodologies and their potential to influence the built environment.

In conclusion, this research has demonstrated the development and implementation of a novel timber-dowel reciprocal lattice system for architectural applications. The key innovations lie in the elimination of commonly used joints and connections, the integration of computational optimization, and the adoption of degradable, reusable materials. The results highlight the potential of this approach to streamline fabrication, enhance structural performance, and promote environmentally responsible design and construction practices. The final prototype as shown in figure 6, and the evaluation of the system suggest its applicability in various architectural and construction contexts.

Figure 6. Photos of one-to-one prototypes next to a human for scale. Left: the prototype features the same lattice structure but utilizes the TDRL system instead of 3D-printed joints. Right: a photograph of the manufactured and assembled prototype using oak wood for oblique dowel elements and plywood for horizontal timber elements.

5. Future work

The application of the timber-dowel reciprocal lattice (TDRL) system to curved surfaces and freeform volumetric systems will be explored in future research. Adapting the TDRL system to complex freeform geometries offers the potential to extend its application beyond standard configurations like the arches presented in this paper. Integration of computational design tools with advanced simulation capabilities is expected to facilitate the design and fabrication of structures with organic, continuous surfaces. In the next phase of research, conducting sets of structural tests and analysis on one-to-one prototypes will further evaluate the structural capacities of the developed method under real load cases. Additionally, the development of freeform volumetric systems is expected to enable dynamic spatial arrangements that optimize environmental parameters such as light and sound, as well as overall embodied energy efficiency. This expansion will likely require enhancements to existing computational models and robotic fabrication techniques to handle the geometric complexity of nonlinear and multidimensional elements. Furthermore, exploring other topological types of voxelization systems using polyhedral tessellations beyond the used tetrahedral-octahedral honeycomb—such as cumulated cuboctahedrons, uniform tetrahedrons or triangular pyramids, and non-uniform polyhedral tessellations—can extend the functionality of the developed methods.

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Paper Title: Timber-Dowel Reciprocal Lattice System: Design Computation to Assembly, Case Study on Tetrahedral-Octahedral Voxelization

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