RECIPROFRAME TIMBER GRIDSHELL

From CAM Data Interface Modeling to Operating Industrial Joinery Machine for Scaling up Reusable Timber Structures

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Abstract. This research extends the work from our previous study on utilizing digital technologies to turn short solid timber elements into framed timber systems designed for the rapid assembly and disassembly of cost-effective, material-efficient, reusable gridshells. In a former paper, we developed an innovative reciprocally-reinforced topology of trivalent polyhedral frames, termed "ReciproFrame", enabled by the development of a CSV file to leverage the precision and speed of multi-axis robotic arms, which was then utilized in the construction of a small-scale, 7.5-meter research demonstrator. Although the multi-objective analysis confirmed the efficiency of the production method in constructing structurally-efficient catenary cross-sections without the need for any steel nodes—a feat not achievable with previous geodesic domes—we realized that the automated construction of larger structures in future timber industry would require an industrial-class production workflow featuring high-performance units equipped with powerful and efficient machining capacities for varied timber processing. As a solution, this paper presents a 24-hour industrial fabrication workflow, enabled by a self-developed data interface plugin that generates XML-based, industry-standard CAM data for the direct instruction of Hundegger K2 machines. It addresses the operational problems and technical challenges related to interoperability between the data interface programming and the operation of industrial joinery machines. Finally, the paper discusses the possible applications and limitations of the production workflow, while presenting the design-to-assembly process of a medium-scale research demonstrator with a maximum span of 15 meters, made of 768 industrially-fabricated Laminated Veneer Lumber (LVL) beams.

Keywords. Automated joinery, XML-Based CAM Data, CAMBIUM, Hundegger K2 Joinery Machines, P-Hex, ReciproFrame, Laminated Veneer Lumber LVL, Reusable Timber Gridshells.

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1. Introduction

Recent advances in Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) data interface modeling for instructing Computer Numerical Control (CNC) machines have enabled timber gridshells, to experience significant innovation, from joinery to assembly processes (Chilton and Tang, 2017). Timber gridshells represent a sustainable and cost-effective approach to lightweight structures that efficiently utilize materials, employing a modular arrangement of linear elements to create a grid topology that shapes a form-active surface. The joint system plays a critical role in gridshells, exemplified by structures with geodesic spherical geometry and steel nodes like the Tacoma Dome in 1983, Saldome1 in 2005, and Saldome2 in 2012 (Bogusch, 2010). Although new CAD/CAM methods have enabled novel metal joint improvements for various timber systems (Naicu et al., 2014), timber joints are still complicated in free-form structures where a multitude of geometrically different connections are required.

As well, despite the varied application of scissor-like timber systems (Gabriel, 2013), which enable a structure to be reusable with a high level of ease and rapid assembly, disassembly, displacement, and reassembly, most large-span timber gridshells are typically built for long-term use, as the process of reusability is highly complicated for two main reasons. First, such gridshells often utilize further hybrid agents like cable and steel connectors to meet the required structural efficiency, which makes the whole disassembly process complex. Second, due to the dependence of the timber system on a multitude of discrete elements, disassembling each single element would be highly time-consuming and frustrating. These two reasons alone convinced us to present our former construction system 'ReciproFrame' - a sustainable timber system for the low-cost, material-efficient, and rapid assembly and disassembly of reusable timber gridshells (Adelzadeh, et al., 2023; Karimian et al., 2023) - at a larger scale where it can prove its fabrication-oriented capacities as a successor to existing plate- or cassette-based timber systems for future gridshell construction with no need for metal connectors.

Formerly, we practiced automation through the development of Comma-separated values (CSV) files for operating a 6-axis robotic setup. Although robotic fabrication has its own benefits, we believed that the former robotic fabrication method should be replaced by industrial production approaches for several reasons. Among all, an industrial production workflow features high-performance units equipped with powerful and efficient machining capacities for varied timber processing and operations on every side of an element without concerning limitations with length, thickness, as well as the density and stiffness of wooden elements which can be increased in large-scale construction. In addition, it eliminates the need for substituting elements after processing, reducing fabrication time and cost while facilitating automation in production. Accordingly, the hypothesis is that through strategizing an automated industrial-class production workflow for operating joinery machines, the future construction of scalable, reusable timber gridshells is facilitated. The article thereby aims to scale up the former research demonstrator by increasing the spans from 7.5m to 15 meters, as shown in Figure 1.

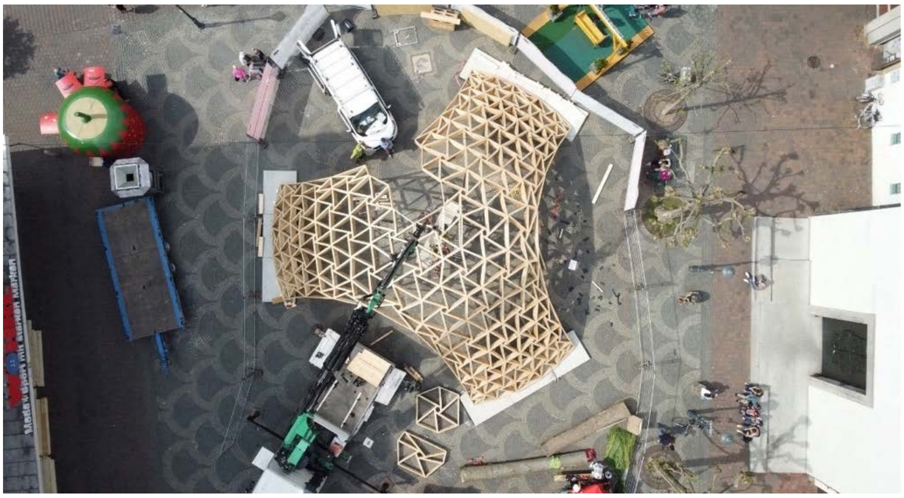

Figure 1. A 15m span research demonstrator: ReciproFrame timber gridshell

2. State-Of-The-Art

Advances in data interface programming have led to the development of IFC-based (Industry Foundation Classes) virtual design and construction software suites for Building Information Modeling (BIM), offering the possibility of IFC-Export for exchange between different timber software applications. These software applications include, but are not limited to, Dietrichs (Dietrichs, 2024), SEMA (Sema software, n.d.), and CADwork (Cadwork, n.d.). Some, like the Woodpecker plug-in for Grasshopper (Woodpecker, 2013), allow for the dynamic translation of parametric models into fabrication data by generating Building Transfer Language (BTL) (Stehling et al., 2014) or (BTLx) - a standard for data exchange between design software and machines, or between different design software (Design2machine, n.d.).

Despite these advances, seamless translation of geometric models into fabrication data models remains complicated in complex timber designs and is mostly limited to research-based projects (Lharchi et al., 2022). This means that in many complex designs with parametric modeling, exporting fabrication data of the joint system might require multiple iterations between design and fabrication software (Willmann et al., 2016) or even remodeling of the geometric design based on fabrication-oriented parameters by timber manufacturing companies (Schwinn, 2016). The process becomes even more challenging when it involves a unique timber system with custom joint details, leaving room for deeper exploration in data interface programming.

3. Methodology

The methodology follows the research structure, which is divided into two parts: computation and construction. As interface programming directly requires adherence to machine instructions, we initially selected the Hundegger CAMBIUM software (Hans Hundegger AG, 2023) which is a single software for all Hundegger machinery. Leveraging our expertise in using CAMBIUM (Robeller and Von Haaren, 2020;

Adelzadeh, et al., 2022), we chose the C# programming language within the Grasshopper 3D / Rhinoceros 3D environment (Robert McNeel & Associates) to develop an algorithm for seamless data exchange between Grasshopper and CAMBIUM. Then, we tailored operations to the Hundegger K2 joinery machine, as it was available in research collaborator company CLTech GmbH & Co. KG. This machine is recognized for its capability to cut various timber elements, ranging from small cross-sections to larger timber elements measuring up to 300 x 1,300 mm.

4. Computation

The first section describes the fabrication-oriented modeling principles, geometry processing, and data interface programming for the seamless translation of geometric models into fabrication data, directly readable by industrial joinery machines.

4.1. FABRICATION-ORIENTED GEOMETRY PROCESSING

Ensuring the readability of fabrication data by joinery machines requires skills in fabrication-oriented modeling to geometry processing. This is essential to avoid unexpected technical issues such as, but not limited to, splits, trims, or intersections between elements. All parts and joint details must be parametrically generated; however, there might be significant differences between geometric and fabrication modeling. Many operations, such as sawing, drilling or slotting, require primitive definitions, rather than complete geometric modeling. In this context, the ReciproFrame has already demonstrated its fabrication-oriented design capacities. Using P-Hex (Wang 2008) for Constant-Distance Offset (CDO) (Robeller and Von Haaren, 2020), disables any nodal gaps or even intersections between end cuts, as studied by Bannwart (Bannwart, 2017). Since most modeling operations and commands, especially in Rhino, are approximate, we specified a 0.01mm tolerance; otherwise, it might decrease the accuracy of exported data. Given this, a 1mm gap has been applied between the cassettes to neutralize any non-planarity of timber beam faces or other deformation during assembly processes. To focus on fabrication data modeling and not the timber system improvement, the joint details remained uncchancged. So, all end cuts and slots, which were used for rapid and accurate alignment of elements, have been modeled as planes, from which the in- and out-of-plane coordinates could be extracted for sawing and horizontal slotting. Although each joint is screwed, no detail is generated, as the screwing has been performed by wood experts with no augmented reality (AR) or robotic assembly involved. Between adjacent cassettes, the application of back-to-back bolt connections required pre-drilling holes. However, only a starting point, vector, and depth have been extracted for milling with a certain diameter slightly larger than the bolt's diameter. This ensures that there will not be any practical issues in inserting bolts. Furthermore, we optimized the geometry of the cassettes to achieve a more uniform distribution of frames and beam sizes and within the structure. Also, the algorithm was further developed to enable more efficient control over the end cut angles of the reciprocal beams. This refinement aimed to avoid acute and long end cuts, considering fabrication constraints, and to prevent tight space that could hinder manual assembly processes, such as reaching both sides of the elements for screwing joints or inserting bolts.

4.2. CAM DATA INTERFACE PROGRAMMING

A pivotal aspect of this industrialization process was the development of a customized CAM data interface modeling tool, facilitating data exchange between Grasshopper and CAMBIUM software. Operating the Hundegger K2 is enabled by CAMBIUM, which requires Extensible Markup Language (XML) data extracted from the geometric model. The software would then be capable of regenerating the fabrication-aware model, as shown in Figure 2. The development of the CAM data interface is divided into several stages. Initially, the algorithm processes the parametric model in Grasshopper and Rhino, discretizing each component of the geometric model. It is adept at extracting primitive data from each component, including, but not limited to, points, lines, curves, vectors, and planes, thereby converting each geometric property into XML-based data. The exportation of data must strictly adhere to guidelines and instructions, as any mistakes in extracting data, like the starting points or directions, could result in operational error. Through this interface, all side and end cuts, as well as slots, were accurately translated into planes and coordinates through which the direction and depth of each cut are readable by the machine. Serving as a vital link between the design model and the industrial joinery machine, this interface ensures seamless and dynamic data translation during the fabrication process. Close collaboration with expert manufacturers at CLTech GmbH & Co. KG enabled us to test and verify the accuracy of the exported data before fabricating the real parts.

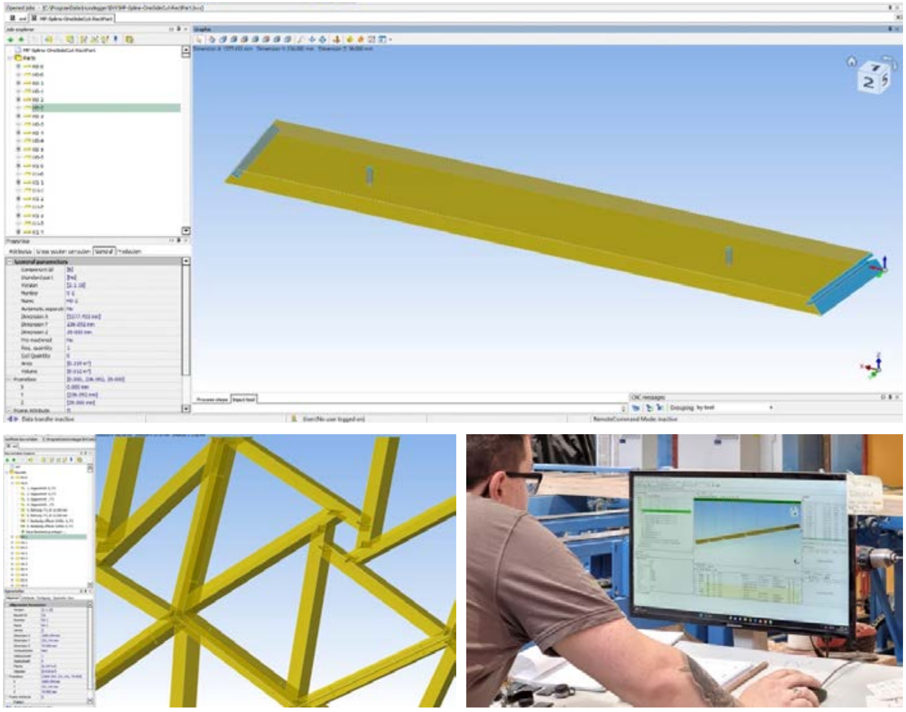

Figure 2. Translation of the geometric data into an industry-standard CAM data through a self-developed XML-based data interface

5. Construction

This section describes the construction process, from the industrial production of elements to the assembly of cassettes. It discusses how the utilization of industrial joinery machines can contribute to design-to-assembly processes in scalable timber gridshell construction.

5.1. AUTOMATED OPERATION OF HUNDEGGER K2

Thanks to the data interface, we were able to continuously operate the Hundegger K2 in three shifts, automating the 24-hour production of timber beams, shown in Figure 3. This facilitated the mass production of numerous elements, while enabling a parallel assembly process. Using joinery machines benefits the production workflow in several key aspects, including time savings, cost reduction, and reduced workforce requirements. The power, speed range, and accuracy of sawing led to the production of high-precision end cuts and slots, preventing potential damage to the wood texture and eliminating the need for finishing. With slot chains of different widths, machining on all four sides of the part was possible, which avoided additional motions like robotic fabrication. During machining, the parts were clamped and moved according to operations, allowing for machining at all angles, inclinations, and length on all part sides without the need for turning timber element or changeover times. With a 13 kW

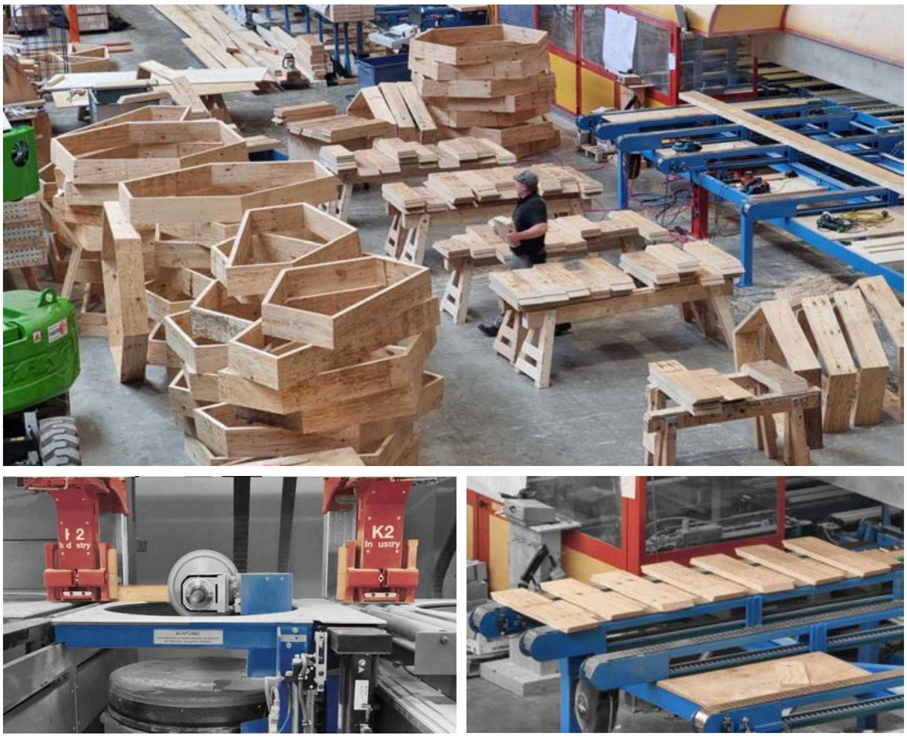

Figure 3. Automated production of timber elements operating Hundegger K2

sawing unit and an open sawing table, we had no limit to performing spatial cuts, even with larger LVL cross-sections. Cuts and slots with different blades were made separately, without any retooling, saving fabrication time, To streamline the parallel assembly workflow and prevent any errors in tagging, the fabrication process began with organizing similar sets in rows. This approach promises a construction system that is not only cost-effective but also fast and straightforward.

5.2. ONSITE ASSEMBLY AND DISASSMBLY

The onsite assembly can be discussed based on the multifaceted benefits of automated machinery in the timber assembly process, highlighting the efficiency, precision, and scalability it brings to construction workflows. Thanks to automation, we were able to enhance production capacity and facilitate the mass production of timber elements with unparalleled precision. This capability is vital for maintaining quality across large-scale projects, where the quantity of materials could otherwise compromise consistent standards. The entire fabrication and indoor assembly of cassettes in the factory occurred concurrently in approximately 2.5 days, adhering to strict construction timelines without compromising quality. This was made possible by the precision and speed of the joinery machine, enabling simple, rapid, and accurate assembly of cassettes without the need for a substructure, clamping, etc., as shown in Figure 4. To further decrease assembly time and cost, the screwing and attachment of cassettes were done manually by wood experts. Thanks to pre-drilling holes with slightly larger diameters and removing tight spaces, inserting bolts were facilitated as expected. Through algorithmic optimization, bad angles and long cuts with potential damage to the wood texture, were significantly reduced. The precision of the joinery machine in implementing side cuts, and the application of a practical 1mm gap, allowed for the control of any tolerances, providing room to neutralize deformation, particularly between some of the last dome cassettes during onsite assembly. Regarding the timber system itself, the uniform distribution of size and planarity of cassettes enabled easy nesting, packing, transporting, and deploying from the factory hall to the construction site. Thanks to such level of accuracy and efficiency in production, we were able to disassemble, displace, and store the entire structure to be reassembled at another place, as planned.

6. Discussion

Operating industrial joinery machines has enabled the realization of a larger version of our research demonstrator, demonstrating a promising future for further integration of digital and physical investigations, stepping towards bridging the gap between research and the timber construction industry. Thanks to development of an industrial-class production workflow featuring high-performance units, we were able to benefit from powerful and efficient machining capacities for varied timber processing. Consequently, we successfully doubled the size of our research demonstrator to a 15m span in a maximum of five days. Regarding our hypothesis, we contributed to the existing context of timber gridshell construction by introducing an industrial production method, enabling new possibilities for accurate, easy and rapid assembly,

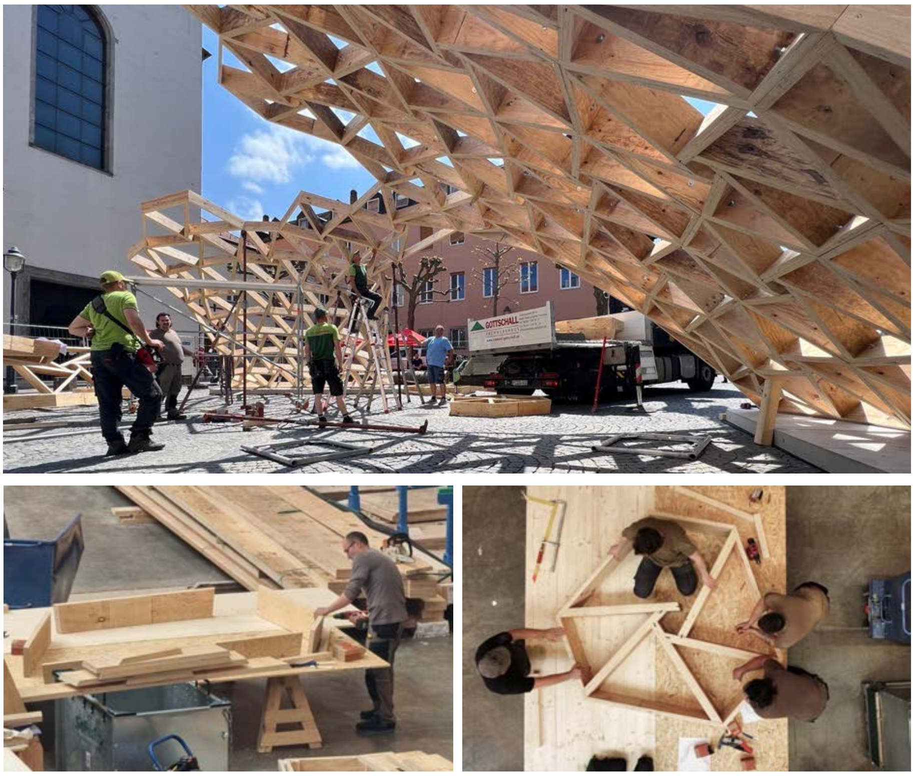

Figure 4. Indoor and onsite assembly of beams and cassettes

disassembly, displacement, and re-assembly of reusable gridshells at different scales. Developing a CAM data interface without any bugs or errors enabled an automated workflow for mass production of elements, offering multifaceted benefits compared to robotic fabrication processes. This development provided a substantial opportunity to reduce production time and cost, which would have been tremendously complicated, time-consuming, and expertise-oriented otherwise. The data interface allows us to use CAMBIUM, enhancing our ability to operate other Hundegger machines and opening new doors to employ other units, equipment, and tools.

We also highlighted the successful integration of digital tools and manual expertise, underscoring the collaborative potential between automated joinery and manual assemblies in advancing timber construction. The advances in design-to-assembly processes would potentially benefit the research context on reciprocal structures, formerly exemplified by previous developments in reciprocal timber systems and joint improvement (Song et al., 2013; Gherardini and Leali, 2017; Mesnil et al., 2018; Apolinarska et al., 2021). Last but not least, to maintain the focus of this paper, the entire design and structural analysis, experimental load test reports, and FEM analysis, verifying the efficient transfer of compression and shear forces down the length of their elements (Adriaenssens and colleagues, 2014), will be published in a subsequent paper.

7. Conclusion

The paper unlocks the fabrication-oriented capacity of ReciproFrame construction system for the easy and rapid assembly and disassembly of low-cost, material-efficient, and scalable reusable gridshells, with no need for steel nodes. The paper adds to the existing context of gridshells by presenting a self-developed XML-based CAM data interface for Hundegger CAMBIUM software by which the timber system can now be automatically mass produced by any industrial joinery machine. The power, accuracy and speed of joinery machines, enables the timber processing of beams with larger length, size, and density with the great possibility easy, rapid, and precise assembly, opening up new opportunities for further application of the joint system in constructing reusable shells with larger spans, Proving that, we increased the span from 7.5 m to 15 m, and the shell's area from 20 to 127 sqm, within a remarkable five-day timeframe.

The next step is gain more benefits from high-performance capacity of joinery machines for improve joint details, particularly in pre-drilling method for application of wood dowels in wood-wood connection system. Moreover, to validate the further capacities of the timber system for free-from structures, construction of a medium-scale anticlastic research demonstrator is planned for summer 2024.

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