Joint Descriptive Modeling (JDM) for Assembly-Aware Timber Structure Design

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Abstract. Joints design is an essential step in the process of designing timber structures. Complex architectural topologies require thorough planning and scheduling, as it is necessary to consider numerous factors such as structural stability, fabrication capabilities, and ease of assembly. This paper introduces a novel approach to timber joints design that embed both fabrication and assembly considerations within the same model to avoid mistakes that might cause delays and further expenses. We developed a workflow that allows us to identify the fundamental data to describe a given joint geometry, machine-independent fabrication procedures, and the assembly sequence. Based on this, we introduce a comprehensive descriptive language called Joint Descriptive Model (JDM) that leverages industry standards to convert a joint into a usable output for both fabrication and assembly simulations. Finally, we suggest a seed of a joint's library with some common joints.

Keywords: Design for assembly · Joints design · Timber structure · Assembly information modeling

1 Introduction

With the rapid advances in computer-assisted design tools and parametric modeling in architecture; designing and manufacturing, and assembling buildings with complex geometry is becoming more accessible, especially within the timber construction field. Simultaneously, digital fabrication machines' proliferation is pushing toward an uninterrupted chain from the design-to-fabrication process (Beorkrem 2017). Complex structures can then be described with an exhaustive parametric model that breaks down the complexity into several separated relatively simple elements and becomes more manageable.

While these parametric models can provide an extensive overview of the design, the seamless translation from design model to fabrication files to assembly instructions is still limited to research and academic fields, where the global design parameters are known in advance (Stehling et al. 2014). In a large-scale project, it is very difficult (and often impossible) to have an overview of different components, fabrication techniques, and logistic considerations during the early design phase. This is because all the stockholders are not known initially, in addition to other aspects such as administration or

tendering that do not get decided until later stages. This requires multiple iterations of the design, particularly in the case of timber structure; where slight changes of the geometry significantly impact the connections that constitute a decisive part of the structure (Willmann et al. 2016) and therefore the fabrication and assembly strategies as a whole. Concepts and tools that support an integrative design procedure are missing.

In this paper, we present Joint Descriptive Model (JDM). This expressive model is intended to represent timber joints regardless of their position in the structure and facilitate machine-independent fabrication data production. Finally, we enrich this model with assembly instructions for a comprehensive design process.

2 Background

2.1 DfMA in Architecture

Design for X (DfX) is a philosophy that has been around for several decades (Boothroyd 1987; Eastman 2012), and aims in general to ensure the quality of products or services and the same time, to optimize the manufacturing procedure and to minimize life-cycle costs (Gatenby and Foo 1990). DfX is a generic term where X stands for any critical considerations during the design, affecting the outcome profoundly. For example, manufacturing (Design for Manufacture – DfM), assembly (Design for Assembly – DfA), testability (Design for Testability – DfT), and many others. Mainly, DfM looks into the optimization of methods and procedures for making or fabricating individual parts, while DfA is concerned with how those parts are put together to constitute the final product. As most products are complex and constituted of several intricate elements, these two disciplines are often considered together and constitute Design for Manufacture and Assembly (DfMA) (Bogue 2012).

Recently, several researchers (Gao et al. 2020; Tan et al. 2020) looked into applications of DfMA in architecture, and while it is present to some degree, it is still arguably yet to be implemented efficiently. Such an approach would be particularly beneficial in timber construction, where it is essential to deal with fabrication processes (both analog and digital) and off/onsite assembly strategies.

2.2 Joints in Timber Architecture

Timber structures are usually composed of multiple elements that are put together onsite with or without additional fasteners. It is essential to think about the connections between these elements. As mentioned earlier, joints play a crucial role; therefore, a particular focus has been given to the design of connections both in academia and industry. In general, we distinguish between two types of joint systems:

- Integral Joints: Elements can be connected and fixed without the need for any fasteners such as finger joints or lap joints (Schwinn et al. 2013).
- Joints with fasteners: Additional elements are needed to fixate the structure, such as bolts or metal plates (Thoma et al. 2019) (Fig. 1).

Fig. 1. Example of a finger joint with additional fasteners (left) and integral joints (right). Source: ICD, University of Stuttgart (left).

While these two types of joints require different design approaches, they are fundamentally similar as they both need extensive planning for fabrication and assembly. Within the scope of this work, we focus on integral joints.

2.3 Assembly Information Modeling

This research builds upon previous work about design for assembly in an architectural context. This work is developed as an extension to an existing framework, “Assembly Information Modeling (AIM)” (Lharchi et al. 2019). AIM is a digital framework that is designed to integrate assembly considerations in the design process. Based on principles from DfA, it aims to include all the necessary data to describe precisely an assembly sequence (including the geometry, directions, sequence, and environment). The flexibility of the model allows many applications such as cloud collaboration or augmented reality assisted assembly (Lharchi et al. 2020). The assembly data is stored in a single model called Assembly Digital Model (ADM). In research, we use ADM as an intermediary container to enrich a classic joint model with assembly data.

The use of AIM allows a description and simulation of the assembly process, and thereby the evaluation of chosen construction and assembly strategies. However, fabrication is inherently linked to these strategies as it dictates the nature of joints that are fabricable. Methods to embed fabrication information in a single model alongside with other data (geometry, assembly, logistics) are still missing.

2.4 Practices in Timber Fabrication

There are many suggested methods to exchange fabrication data within the timber industry. This is achieved exceptionally well by the Building Transfer language initiative.

Building Transfer Language (BTL) is an open standard that is developed and maintained by SEMA and CadWork. It provides a parametric description of the geometry of a timber building component (Al-Qaryouti et al. 2019). There are two available variants: BTL and BTLx. The latter is an improved version of the former, and offers a modern XML-based syntax. BTL is purposely not machine-specific, and the processing is defined through the results rather than the actual machining process (Stehling et al.

2014). This machine-agnostic approach releases the design from requiring a precise machining environment at the time of design (Fig. 2).

Fig. 2. Machining operations as described by BTL. Source: <https://design2machine.com>.

Many CAM software packages adopt BTL, but very few CAD modeling software offer usable interfaces to analyze geometry features and export them to BTL. Woodpecker (Stehling et al. 2014) is a free plug-in for Grasshopper¹ and is used for BTL export. Overall, the process of design should focus on ensuring a seamless data flow from CAD to CAM (Tamke and Ramsgard Thomsen 2008).

3 Methodology

To provide a generic model capable of describing the geometry of a joint accurately, independently from machine specifications, and at the same time to include assembly information, we looked at existing practices within timber fabrication to identify a base for our proposed language. Based on standard industry representations, we defined a set of extendable specifications. Finally, we provided a seed for a joints catalog that can be used to speed up timber structures' design process.

3.1 Timber Machining Methods

We classify machining methods in timber into three categories:

- Task-Specific machines: Machines capable of doing unique tasks with high accuracy and repeatability (e.g. drilling, cutting).
- 2D/2.5D CNC Routers: Also known as CNC cutting or milling. It is the most commonly used fabrication technique. A simple 2D drawing is used as an input; the machines can generally make contouring, surfacing, and drilling.
- Special Machine
- Generic multi-axis machines: This also includes industrial robotic arms. These machines are capable of milling complex joints and run consecutive operations with different tools.

¹ <https://www.rhino3d.com/>.

To support exporting machining operations, we considered AutoCAD DWG and AutoCAD Drawing Exchange format (DXF). While DWG is more advanced and supports more features, it is proprietary and requires specific licensing models. Therefore, DXF format was chosen to represent 2D and 2.5D operations. All other machining operations are exported using the BTL presented earlier.

3.2 JDM Implementation

The proposed JDM implementation is divided into two parts: The first part “JDM.Core”, is a tool that analyzes intersections in the structure (curves and vectors) and is capable of generating the joint geometry. The second part analyzes the geometric features of the said joint, and generates a corresponding BTL file.

The JDM.Core library was written in C#², a powerful object-oriented programming language that leverages the .NET Core Framework. While the core library can run on different operating systems (Windows, Linux, macOS), we focused on the Windows Platform and Grasshopper environment to demonstrate the potential of the proposed method.

To generate BTL files, we used the Grasshopper plug-in “Woodpecker” presented earlier (Stehling et al. 2014). As there is no available plug-in Application Programming Interface (API), we used an intermediary interface exposed by Grasshopper “Ghpython-lib.Components”. This interface allows direct interaction and scripting for installed plug-ins even if an API is not exposed.

The model specifications and the implementations sources and binaries are available online on this repository: <https://github.com/ALharchi/JointMaker>.

3.3 Joint Library

One of the goals of this research is to provide a base for designers to facilitate the design of timber structures. This can be achieved by providing a catalog of timber joints that can be used within a parametric model. The joints can be adapted to the structure and incorporate various limitations such as maximum angles and minimum sizes. Users can

Fig. 3. Different joints types implemented in the library

² <https://docs.microsoft.com/en-us/dotnet/csharp/>.

specify nodes within the structure and then can choose an appropriate joint from a given catalog. Adding more joints to the library is possible using a JDM definition.

We defined three joints types to demonstrate this feature: Half Lap, Cross Half Lap, and Corner Half Lap (Fig. 3).

Nodes in the structure can be replaced with joints that are already enriched with fabrication and assembly data. Export as BTL, NC, DXF for fabrication or ADM for assembly simulation is then possible. Figures 4 and 5 illustrates an overview of the process and the final result as viewed in BTL Viewer software.

Fig. 4. Automatic Joints generation from nodes in a wireframe structure

4 Result and Discussion

The outcome of this work is a novel joint representation that focuses on timber construction. This representation allows embedding both assembly and fabrication consideration in one single model. The implementation (Fig. 6) of the method within the CAD software offers an effective tool for designers to iterate quickly over different design options and have realistic expectations about the fabrication and assembly to assess design choices.

Further development of this work should focus on the expansion of the joints catalogue and the integration of structural properties.

Fig. 5. BTLx as viewed in BTL-Viewer³

Fig. 6. Integration of fabrication and assembly to inform the global design

5 Conclusion

This paper has demonstrated that the combination of machine-independent fabrication representations and assembly digital models constitutes a powerful tool to go rapidly through design iterations, simulate the assembly and digital fabrication, and finally prototype and fabricate timber joints. We showed potential usages of the JDM-powered joints catalog and workflows from design to assembly and how it can allow a seamless transfer of DfMA principles between the different stakeholders.

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³ <https://design2machine.com/btl/viewer.html>.

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