Timber Joints Analysis and Design Using Shape and Graph Grammar-Based Machine Learning Approach

Synthetic Data Preparation of Timber Joints' Shape and Graph Grammar for Machine Learning Application

Ho Man Yau[1], Theodoros Dounas[2], Wassim Jabi[3], Davide Lombardi[4]
[1, 2]Robert Gordon University, [3]Cardiff University, [4]Xi'an Jiaotong-Liverpool University
[1, 2]{h.m.yau | t.dounas}@rgu.ac.uk, [3]jabiw@cardiff.ac.uk, [4]davide.lombardi@xjtlu.edu.cn

Timber joints had been applied as one of the primary methods across different cultures of building construction. The technique of crafting timber joints uses simple geometry to connect different components without the need of adhesives or fixings. Digitalisation and computational design method provided a new approach to developing complex timber joint connections. By combining this traditional technique with computational design methods, shape, and graph grammar opened new opportunities in reinterpreting timber joint designs. In this paper, we proposed a timber joints' synthetic dataset preparation using shape grammar and graph grammar for machine learning applications. The research focused on designing a prototype of a shape grammar extraction system and graph extraction system manually and using Topologic in Sverchok, Blender, with a discussion on how to shape grammar applications help to analysis and create a larger database for future machine learning development of this project.

Keywords: *Shape grammar, Graph grammar, Timber structures, Parametric design, Machine learning.*

INTRODUCTION

Digitalisation has been introduced to the architecture and building construction industry. The technological advancements opened new opportunities in analysing and designing complex geometrical structures. Machine learning (ML) and Artificial Intelligence (AI) applications have become a trend in computational design methods in architecture, in the section involved data-based could be computerised and automated to enhance design practice (Carta, 2020).

This paper investigates how shape and graph grammar open new opportunities creating a more convenient system for the analysis and design of parametrically-based timber joints. By using shape and graph grammar to analyse parametric timber joints for preparing synthetic datasets for ML application (Figure 1). Moreover, this paper will propose a prototype that focused on graph extraction in creating synthetic datasets using traditional timber joints.

This article is divided into the following sections. In the first section, we deliver the introduction and the background of the research. We review which type of tools are needed for the preparation of the prototype for the graph analysis system. In the second section, we propose a graph grammar extract system that is aimed at analysing and translating parametric timber joints into a graph format. We demonstrate the approach of the algorithm, rules, and method being applied to recreate the timber joints. With a shape grammar extraction system and divided into stages to demonstrate on the method of analysis and extraction of rules used in timber joints. The next section shows and discusses different graphs and shape grammars extracted from the algorithm and shapes grammar-generated timber joints. The last section discusses the method, the limitations of the project, and further work of the research.

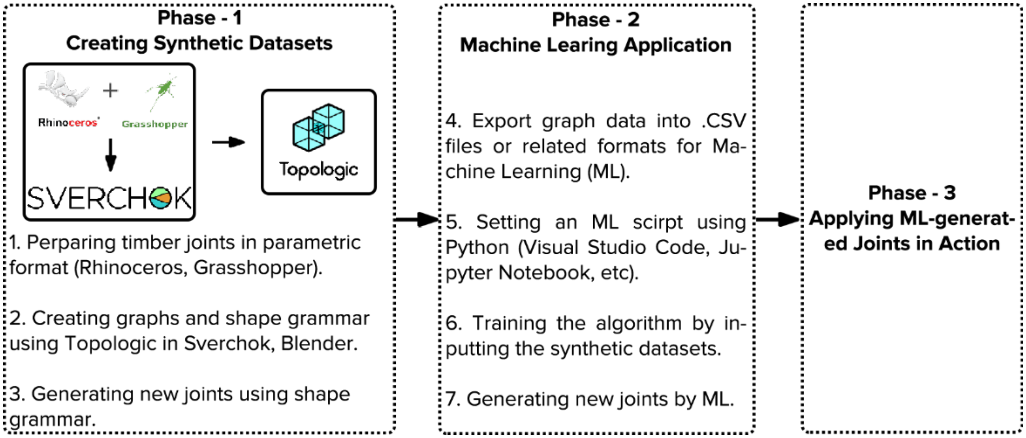


Figure 1
The overall structure of the project

BACKGROUND

Timber has been applied as a primary building material across different cultures for centuries (Yen, 2012). This technique can be traced back to the Hemudu period in China (Fan, 2018). Traditional timber joints used simple geometry to create tight-fit connections between tenon and mortise parts that can be resisting shear and bending stresses. Moreover, some of the wood joints will use draw wood pins to interlock tenon and mortise to create a strong structure. This technique was performed and was well-developed by carpenters in order to create functional and as well as aesthetically appealing joints (Mulligan, et al., 2014).

Different research teams (Heesterman and Sweet, 2018; Takabayashi et al., 2016; Zhao et al., 2022, 2021) researched the potential of translating traditional timber joints for robotic fabrication using parametric design. Introducing parametric strategies for timber joint designs offers a new opportunity for re-introducing this method for building construction by applying modern technology. Takabayashi and his team (2016, 2018), and Böhme and his team (2017) carried out projects in digitating and robotically fabricating timber joints for architectural heritage conservation that used timber joint structures. Heesterman and his team (2018) and Larsson (2020) proposed a method for converting timber joints into curve form and customising geometrical joints that can be adapted by CNC machine production.

Research Aims

As the craftsmanship of traditional timber joints requires experience and extensive skill, traditional methods have been gradually replaced by industrialization (Risatti, 2007). Due to the versatility in shape and form of joints, assigning the right joint to maximise performance is a complex and difficult task, as the craftsperson intrinsically. Different researchers (Heesterman, 2018; Böhme, 2017) investigated how to re-introduce timber joints using contemporary technologies. Translating the timber joints into a parametric design may benefit timber building construction and also the architectural heritage conservation of timber structures. The customisation and flexibility of digital design allow timber joints to be produced by robotic fabrication.

Furthermore, in today's timber industry, there are increasingly advanced and specialised woodworking machinery being offered. Consequently, if the details and information of timber joints can be translated into a parametric model, they would be able to be fabricated by professional timber fabricators. This approach has the potential to contribute to mass-produced timber structure fabrication. Therefore, how can ML application be an alternative approach to analyse and suggest suitable timber joints for the intended timber structure design?

In this study, we focused on analyse on existing timber joints by utilising shape and graph grammar to analyse and generate new designs of timber joints. We also investigated how to incorporate topologic to generate data for ML. We assess the following hypothesis and a design prototype is proposed. Therefore, this paper covered this area of research:

- Investigate what tools and methods are needed to extract shape and graph grammar from timber joints;
- Explain how to generate topologically different timber joints using shape and graph grammar to expand the library of synthetic data.

Shape Grammar

The concept of shape grammar (SG) was proposed by George Stiny and James Gips (Stiny, and Gips, 1972; Stiny, 2006). SG is a design method that is a rule-based production system, this method can be applied to shape rules and generation engines (Celani, 2000; Dounas, 2020). SG employs a series of rules and applies them step by step to generate a design language (Eloy, and Duarte, 2013). SG is a powerful system that is capable of generating an infinite number of designs and leads to different combinations of output. However; due to its non-deterministic nature, SG requires detailed rules in order to determine priori the design output in advance (Celani, 2000).

Graph Grammar

SG is commonly applied in illustrations, while graph grammar finds its primary application in computation (Grasl, 2011). Graph Grammar (GG) is a powerful tool for capturing the structural aspects of shape (Heisserman, 1994), and it contains topological information about the model (Grasl, 2011). GG uses mathematical structures to analyse the relationship between models (Alymani, et al., 2022). The structure of the graph was created by nodes and edges. Nodes represent the data of vertices, lines, surfaces, and Edges represent the relationship between different elements in the model (Alymani, et al., 2022; Aghabayli, 2021).

Topologic

Topologic (Jabi, et al., 2021, 2022) is a modeling software library designed for analysing the topological representations of spaces, buildings, and objects in 3D parametric modelings. TopologicCore includes Topology, Vertex, Edge, Wire, Face, Shell, Cell, CellComplex, and Cluster (Figure 2). Vertex represents an area in 3D coordinate values. Edges are created by connecting the starting and ending Vertices, and Wires join several Edges together. Faces are created by a collection of closed Wires; several connected Faces create Shells. Cells created by closed Shells, by connecting several Cells that share Faces create Cellcomplex. Clusters group Topologies of all dimensions. A Graph representation has been created by Topologies (Jabi, et al., 2022).

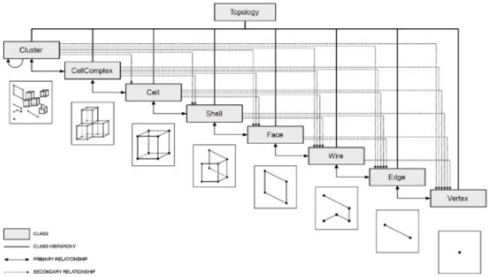


Figure 2
Class Hierarchy of TopologicCore

METHODOLOGY

We are using design science research and computation prototypes in investigating the potential of analysing timber joints using shape and graph grammar-based ML systems. This system aims to explore shape and graph grammar applications in translating timber joints and preparing synthetic datasets for the early stage of ML stage. This system is a design prototype that serves as the foundation of future development in robotic fabrication. This paper shows the process of creating a graph extraction system in Sverchok, Blender using Topologic. The structure of the system is divided into the following sections: import timber joints (.obj), creating CellComplex, setting dictionaries, assigning dictionaries to Cells, and extracting graphs.

We selected a series of traditional timber joints to serve as a sample for this project. The selected timber joints were transformed into a parametric format using .obj format. The models will be fed to Sverchok, Blender, and later sent to Topologic to be translated into graph form to become the database of the ML algorithm. In the following section, we show the method being applied in transforming traditional timber joints into parametric form, followed by the demonstration of the scripts in Topologic in order to transfer the joints into a graph format. Then we demonstrate the graph outcome that is being analysed and generated by the script.

The Initial Phase of The Research

In the initial phase of the research, we investigated transforming traditional Japanese timber joints for robotic fabrication using parametric design. The primarily of production of parametric timber joint designs was mainly focused on using 3-axis Computer Numerical Controlled (CNC) machine.

The Pole Tenons with Housed Dovetailed Joint is one of the selected joints being tested and translated. However, one of the difficulties encountered with this joint is the internal concave on the column which the 3-axis CNC machine is unable to produce. Therefore, during re-designing, the column was divided into two components (Figure 3) and the Housed Tenon and Mortise Splice were applied as the fixing of two elements.

This investigation shows the possibilities of how traditional Japanese wood joint structures can be designed into the parametric design and process of CNC fabrication.

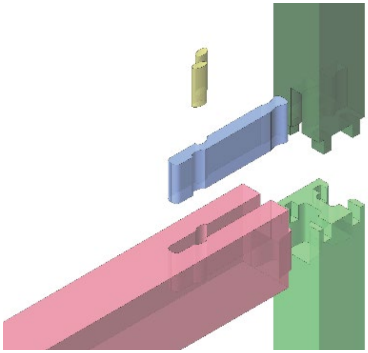


Figure 3
Parametric design of Pole Tenons with Housed Dovetailed Joint
Red: Beam
Dark Green: Upper Section of Column
Light Green: Lower Section of Column
Blue: Spline Tenon
Yellow: Pins

Translating Timber Joints

A total of 14 traditional timber joints were tested for this paper, 9 joints that are dovetailed-related, and 5 splice-related joints were selected for this project (Figure 5). These selected joints were recreated using Grasshopper, Rhinoceros. Vertices that contain XY coordinates were created and connected to generate the boundary of the surface. The surface was then extruded along the Z-axis to create the object of the joint. By manipulating different coordinates which can adjust the length, placement, and direction of the object to create the form that the joint needs. The joints were exported in .obj format and imported into Sverchok, Blender for further analysis.

Extracting Graph Dataset from Topologic

The process of extracting the graph dataset was divided into six sections. First, the .obj files were imported. Then, creating CellComplex, assigning cell dictionaries with transfer dictionaries to the cell of the CellComplex, creating the selectors corresponding to the correct dictionaries, generating, and extracting the graph, and exporting graphs to .csv files (Figure 4).

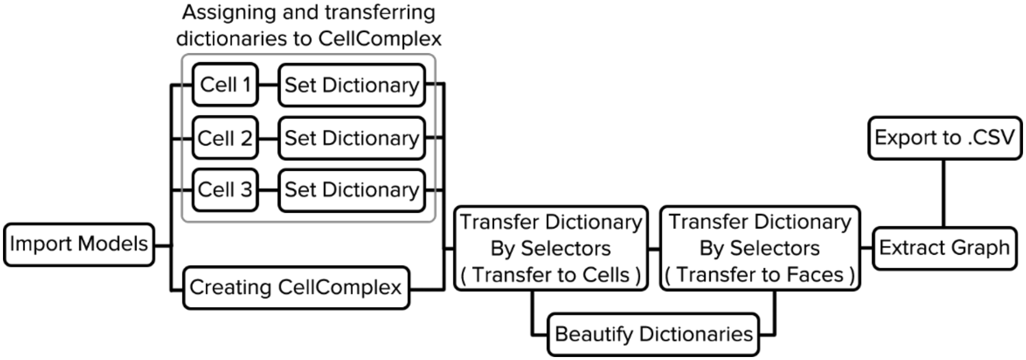


Figure 4
A diagram of the overall structure of graph extraction system

In this project, two categories of timber joints were being tested, 1-9 dovetail joints related and 10-14 splice joints related (Figure 5). These two types of joints were commonly applied in beam, column extension, and beam–column connection. Then using Topologic extracts graph grammars, allowing for the collection of synthetic data to be used as the input for the ML algorithm.

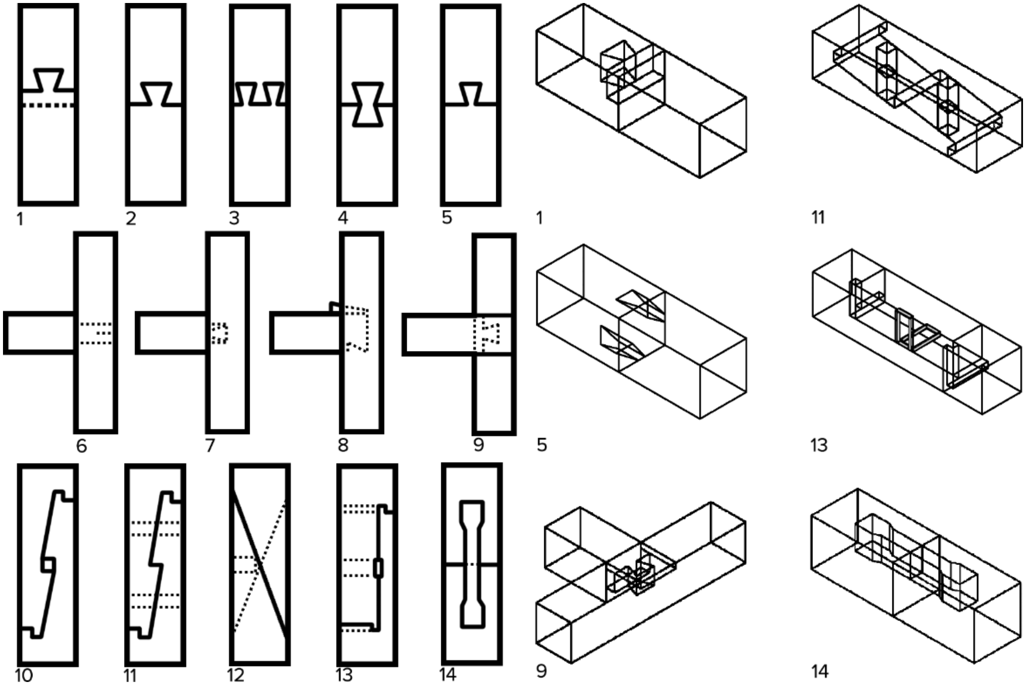
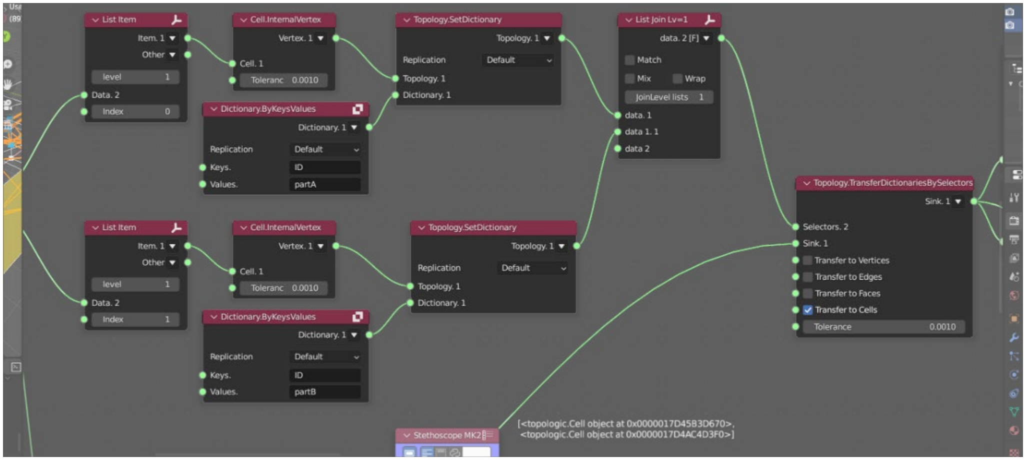


Figure 5
Selections of timber joints used in this testing (2D and 3D)

The presented script is used to analyse and extract graphs grammar from the selected timber joints. In Figure 6, by using "Topology.SetDictionary" to assign labels for the component of the joints such as 'partA', 'partB', 'pinA', etc. These labels help to identify the relationship of the component in the level of vertices, lines, and faces.



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[<topologic.Cell object at 0x0000017D45B3D670>,
 <topologic.Cell object at 0x0000017D4AC4D3F0>]
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Figure 6
Demonstrating method in assigning dictionaries using "Topology.SetDictionary"

Next, the dictionaries were assigned to the cells for creating the cell relationship data using transfer dictionaries by selectors (transfer to Cells) such as 'PinA_partA', 'partA_partB', etc. Once the cells were named, then the data were fed to transfer dictionaries by selectors (transfer to Faces). This step allowed for analysis of the topology and the relationship between each cell and in between cells. As a result, this script is able to generate the graph grammar of joints. The generated data can be exported as .csv files, making them suitable for ML applications.

STRATEGY FOR SYNTHETIC DATA AND FUTURE DEVELOPMENT

The Sverchok, Blender script used to test and extract graphs from the timber joints is available on GitHub [01].

Using the computation prototype we proposed, we tested and translated a total of 14 timber joints, 9 joints that are dovetailed-related and 5 are splice-related joints. During the early stage of our research, different methods and theories were being explored. We observed that increasing or reducing the sizes and adjusting the angle of the joints only creates geometrical differences rather than topological differences. In order to achieve a good result for the future development of ML algorithms, topological variety is one of the key aspects in gathering information for the system. The application of SG can generate a broader range of topological varieties of joints, thus expanding the dataset.

For example, the top left 1st and 2nd joints (Figure 7) which are the stepped dovetailed joints, and the dovetail joint are based on the geometry which contains similar elements. However, the output of the graphs was different, the stepped dovetailed joint contains more nodes and edges compared to the dovetailed joint. Having a more complex geometry and number of components leads to a more complex graph.

In this paper, we also conducted experiments using SG to analyse and extract the elements from timber joints. Figure 8 shows two joints, Stepped gooseneck Joint (male), and the Rabbeted oblique scarf joint was selected as examples to illustrate the process of analysis and the extraction of SG rules applied in these joints. Through a series of extraction, there are different approaches of SG that can be used to achieve the same result. Moreover, due to the inherent non-deterministic nature of SG. It is essential to restrain the rules to avoid generating joints were non-functional designs. Therefore, we decided to follow the common crafting method used to craft such joint as the approach for the rules' extraction. In Figure 8, the extraction system is divided into 4 sections.

Sections 1 and 2 were tracing the common approach of materials removal, by creating dictionaries based on it. In section 3 showcase the base rules (Rule As) to serve as the starting point for the process of SG. Following section 4 was embedding rules (Rule Bs, Cs, and D) to carry on the following stages of creating the joint. These extracted rules are not only used for the recreation of joints digitally but also the feeding the data of recrafting the joint manually or with machinery. By using these SG rules, we will able to help in exploring and establishing a more efficient fabrication method.

Subsequently, we explored 2 approaches of 2D GG to analyse the connections between faces, and lines allow us to extract the relationships between elements. Each node within the graph represented the data of shape that helped to create the joint. By combining various rules combinations, we were able to generate new designs for timber joints (J1-4, Figure 8). Therefore, the combination of SG and GG application demonstrates the potential for generating new reasonable design of joints through the systematic application of rules.

In the future development of the SG application, using SortalGI (Stouffs, 2020), and Biber (Torabi, 2022) could be beneficial in helping to generate new designs and translating the output into 3D models in order to create new joints. SortalGI is a Grasshopper plugin specialised in SG, feeding curve(s) to create rules and generate new designs. It provides a powerful tool for expanding the variety of timber joints. On the other hand, Biber also is a Grasshopper plugin that specialised in creating parametric timber joints by feeding customised shapes. Combining these two plugins might benefit expanding the synthetic dataset of timber joints. These tools had the potential in contributing to the creation of synthetic dataset for timber joints.

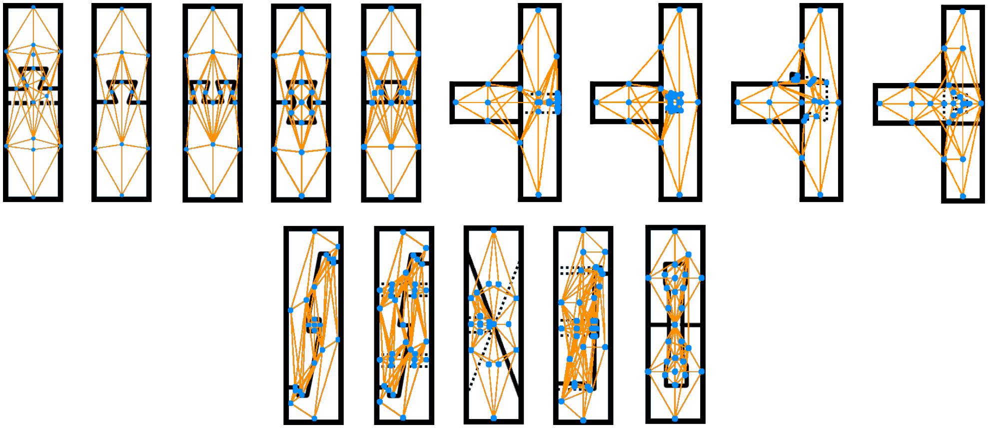

Figure 7
Graph (elevation) of the selected timber joints

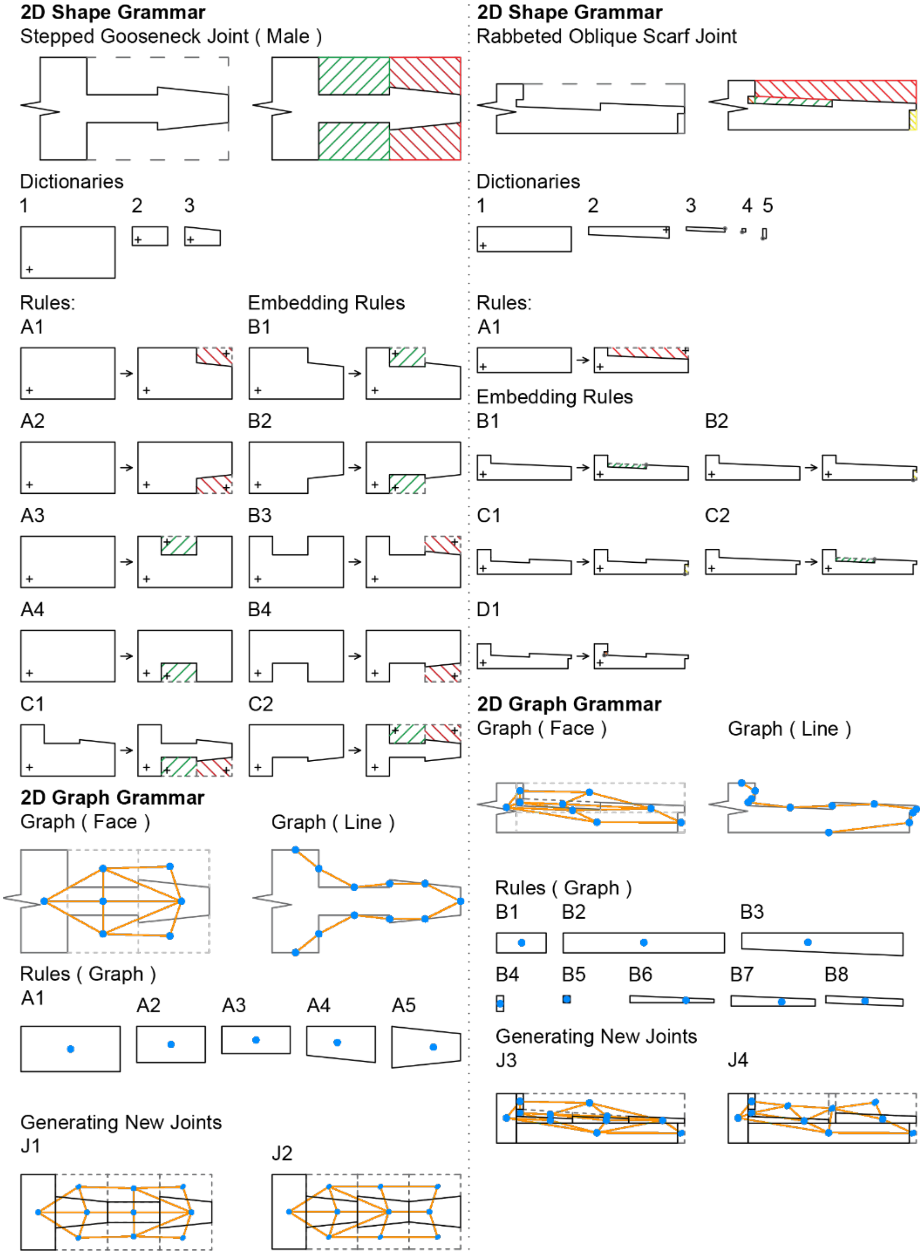

Figure 8
SG rules extraction method, and GG generating new topologically different designs.

CONCLUSION AND DISCUSSION

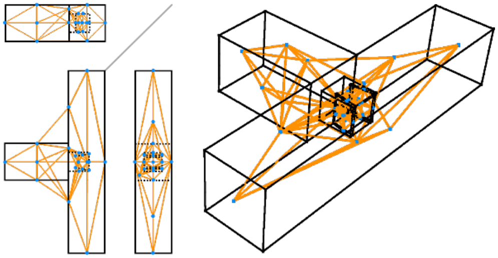

Figure 9
Example: Elevations and 3D of blind wedging joint with graph

In this paper, we proposed design science research and computation prototypes using shape and graph grammar to generate, analyse, and extract graph grammar. This proposed method is designed to gather synthetic data of timber joints for ML application. It also presented the section on the graph extraction system and demonstrated the results of the graph extraction script using Topologic in Sverchok, Blender to analyse and extract graphs from the imported timber joint models (Figure 9).

Additionally, we explored SG extraction with GG to generate new topologically different joints. Although in this paper the joints were being explored manually, still it shows the potential of SG extraction approach and GG application to generate new series of joints. Therefore, in the future investigation of SG and GG applications will focus on refining and constraining rules in order to generate more functionally and topologically different designs of joints. Moreover, adding the simulations of load performance into consideration during refining rules may be able to achieve a better performance of SG, and GG generated timber joints.

The results obtained in the research showed the design prototype of the graph extraction system is able to analyse and extract timber joints into a graph format. Further exploration is warranted to investigate the potential benefits of SG for extracting rules and GG application in gathering synthetic datasets for training the ML systems. Moreover, another criterion of future development is to explore which type of ML algorithm suits generating functional timber joints. By investigating more in these areas, a more comprehensive understanding could be achieved.

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