Timber Joint Connections, Generative Design Method

A topological system approach

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Timber joint connections have been applied as a primary building construction, using concave and convex shapes to connect two or more elements. This research investigated the possibility of using graph-based theory knowledge to analyse timber joint connections. A topological extraction system was developed using Topologic and Karamba3D in Grasshopper. A collection of timber joints was analysed, and the topological relationships, load distribution, and shared face of connections were extracted. The proposed system generates an early-stage knowledge graph integrated with external simulation results. Moreover, in this study, a rule-based generative design approach has also been explored in generating complex timber structures. In this paper, a topological extraction system with external software implementation was developed, and generative design was explored to maximise the potential of the timber frame structure.

Keywords: *Timber Structures, Timber Joints, Graph-Based Theory, Knowledge Graph, Generative Design, Rule-Based Production System*

INTRODUCTION

Timber joint connections follow various rules by adding and subtracting different geometric principles to create concave and convex connections. The geometric forms and principles of timber joint connections lend themselves well to a rule-based generative design language. Applying rule-based generative design languages, such as shape grammar, offers an alternative exploration approach to generate design possibilities (Stiny, 1972). Building on this, Grasl and Economou (2011) integrated graph-based techniques with rule-based grammar to analyse more complex design and architectural languages. The graph-based methods have proven effective in analysing and extracting the structure and information of the elements (Jabi, et al., 2022), further expanding the potential for innovation in timber joinery and beyond.

This paper is structured into the following sections: an introduction, a background and literature review, and a computational prototype. It reviews previous research on generative design and graph-based systems, emphasising studies reinterpreting traditional craftsmanship techniques and architectural design. A computational prototype was proposed, experimenting with the proposed method to understand how to extract the logic behind timber joints using graph representations (Figure 1). This study demonstrates the algorithmic approach and techniques used to extract, analyse, and generate the graph containing information. Then, further work could be discussed to maximise the potential of the proposed system.

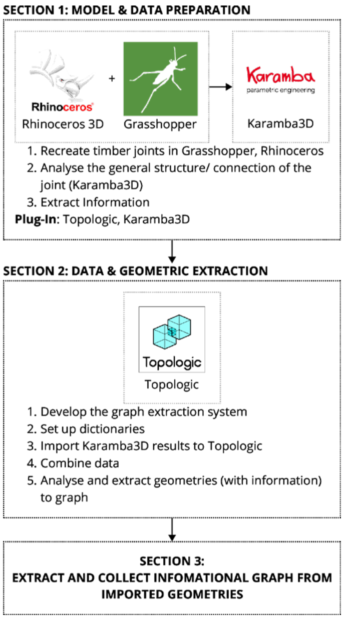


Figure 1
The overall structure of this study

BACKGROUND & LITERATURE REVIEW

Recent studies highlight the potential of computational design tools for deriving alternative approaches to explore innovative timber buildings that are more complex, flexible, and adaptable (Larsson, 2020; Retsin, 2019; Heesterman, 2018; Böhme, 2017). Moreover, incorporating parametric tools and complex structures, such as timber joint connections, can be explored through traditional architectural perspectives and topological representation methods.

Generative Design Method

Rule-based production systems such as shape grammar (SG) and graph grammar (GG) are used as design methods, applicable to shape or structural aspects of shape rules and generation engines (Knight, 2000; Dounas, 2020; Heisserman, 1994). Both grammars use regulations to create a design language (Eloy & Duarte, 2014). This approach is versatile and enables unlimited design variations and different output combinations. A computational design workflow focused on discrete timber frame systems developed by Xu (2024). The proposed system used timber joints and shape grammar to incorporate traditional Chinese architectural principles. A digital timber joints library is being developed, and shape grammar is used for the digital design. The framework shows the potential of design that preserves traditional craftsmanship while enhancing adaptability. A rule-based generative framework for designing interlocking connections using translational and rotational motions has been introduced by Gilibert (2022). The study used a Markov process combined with turtle graphics to generate interlocking polygonal elements. Translational and rotational degrees of freedom are designed through geometric constraints, ensuring interlocking properties.

Graph-Based Theory

The graph-based theory is a combination of various mathematical models used to represent the relationship between objects. To construct a graph, one needs two key elements: a set of points (vertices) and, lines that connect the points (Jabi, et al., 2023, 2022; As, 2018). A pre-knowledge graph study by Lin (2022) used a topological system to analyse the Dougong connection. The study was investigated using Rhino, Grasshopper, Syntactic, and Wasp to analyse and visualise the relationships between Dougong components while exploring the structural properties. A knowledge graph and analysis of force transmission diagrams were collected. This research investigated the topology of Dougong, which enables the design of modular configurations. A graph-based representation of architectural floor plans and an understanding of the relationship between rooms were explored by Chaillou (2020). The study used Bayesian modelling to generate adjacency graphs and to bridge architectural design with AI-driven generative tools.

Research Aims

With the integration of computational tools, timber joint connections can be viewed using traditional architecture and the topological representation method. Moreover, recent research highlights the possibilities of utilising the graph-based theory method to analyse and extract the relationship between elements. Currently, most research focuses on the relationship of components, but little research explores bridging both objects' information with the extracted graphs.

Continuing previous research (Yau, 2023) in exploring the potential of analysing the topological relationships between objects, this paper investigates the possibility of bridging both pieces of knowledge using topological representation to understand and extract the logic of design.

This paper addresses the following research questions:

- How does a graph represent the function of geometries?
- How can timber joints be analysed and imported into a graph in a visual programming language environment?

explores the rule-based generative method with timber frame structures.

In this project, a collection of 13 timber joints from different regions that are commonly applied in timber frame construction was tested using the proposed approach. The selected joints followed the guidance from books written by Sumiyoshi (1991), Shimoyama (2020), Beemer (2016), Zwerger (2023), and Liang (2006). These joints were categorised into four rules: Rule 1: Extension; Rule 2, L-shape; Rule 3: T-shape; and Rule 4: Complex connections (Figure 2).

This study used Topologic and Karamba3D (Preisinger, 2013) to explore and construct timber joint connections. Topologic (Jabi, 2024) is used to analyse and extract the relationship of components. Karabam3D, a parametric engineering solution, is applied to study the loading aspect of the imported structure.

The knowledge graph extraction system process was structured into three main sections: 1.) Model creation and importation. Joints were constructed, and then the sequence was organised along with the Z-axis; 2.) Karamba3D analysis. Joints are analysed, and then the results are imported to Topologic. 3.) Topologic extraction system. Generate and visualise the graph and import information from Karamba3D into the graph (Figure 3).

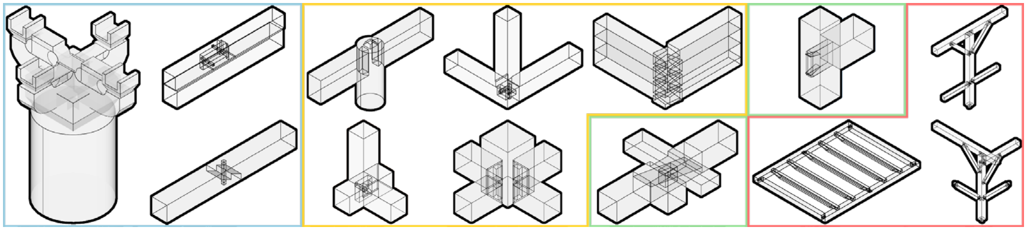


Figure 2
Rule 1: Extension (Blue); Rule 2: L-shape (Yellow); Rule 3: T-shape (Green); and Rule 4: Complex connection (Red)

METHODOLOGY

This study applied design science research with a computational prototype to develop a knowledge extraction system that is capable of extracting the logic and relations of the joints while importing external information. The proposed system aims to explore the preparation of a knowledge graph using Grasshopper. The following section

WASP is a geometry-generative plug-in in Rhino developed by Rossi (2024) and focused on representing and designing with discrete models. It allows the generation of various combinations following rules and grammar. This helps to explore various frame combinations.

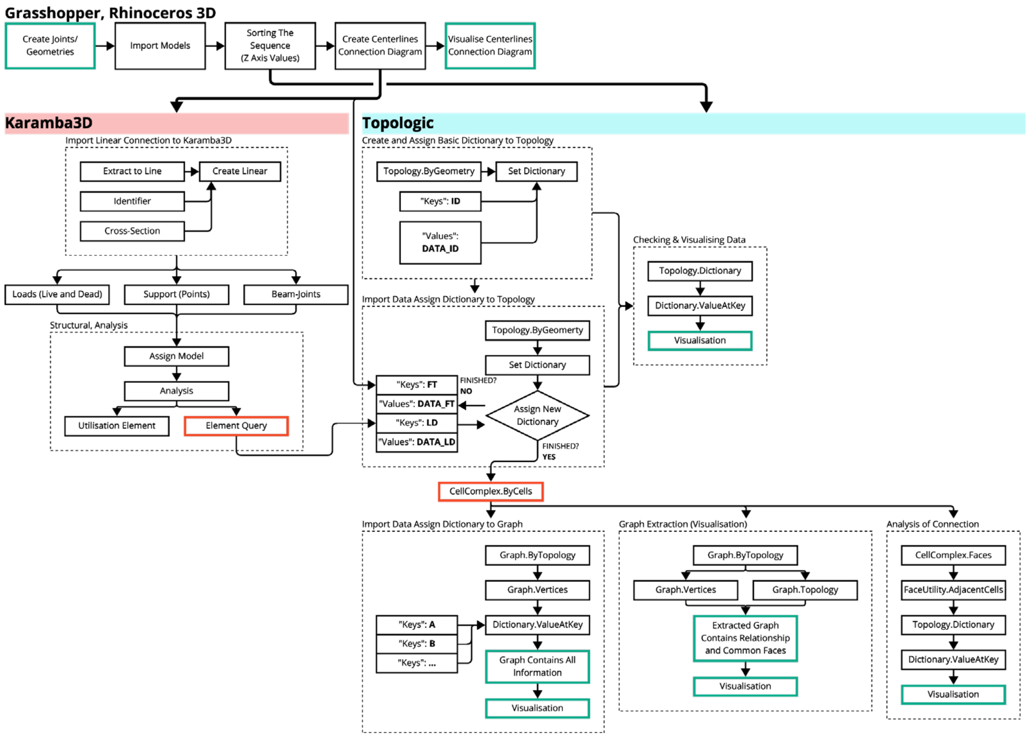


Figure 3
The swimlane diagram of the graph extraction system in Grasshopper, Rhino

RESULTS

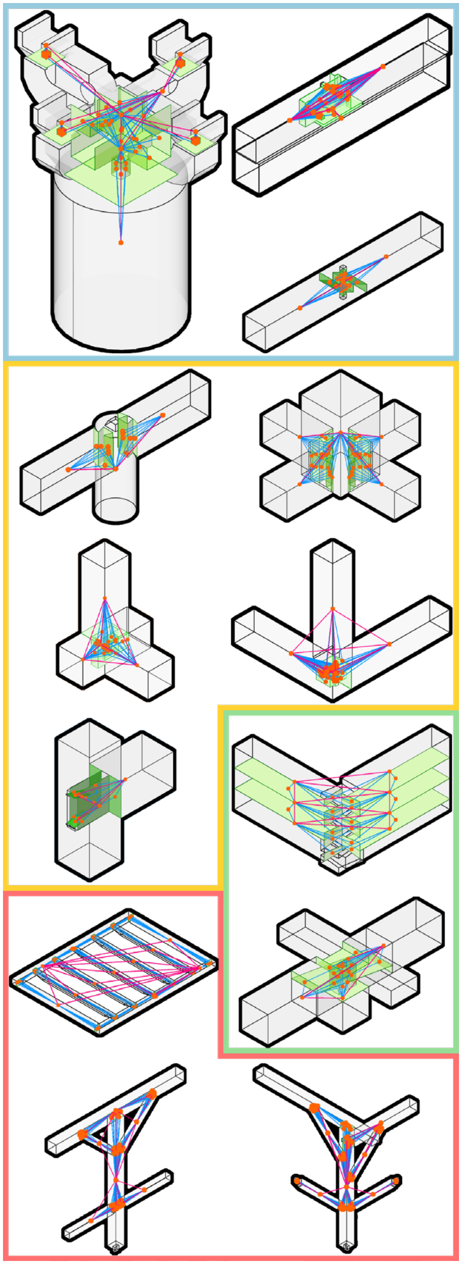
This paper proposed a graph extraction system computational prototype, proposing a potential approach of introducing an early-stage framework of knowledge graph extraction using Topologic. A total of 13 commonly applied timber joints in timber frame construction were created in Grasshopper. A novel topological extraction system was developed to analyse the interconnection of the joints. The following sections elaborate on the topological representation of timber joints, detailing how external information is imported into the knowledge graph accordingly.

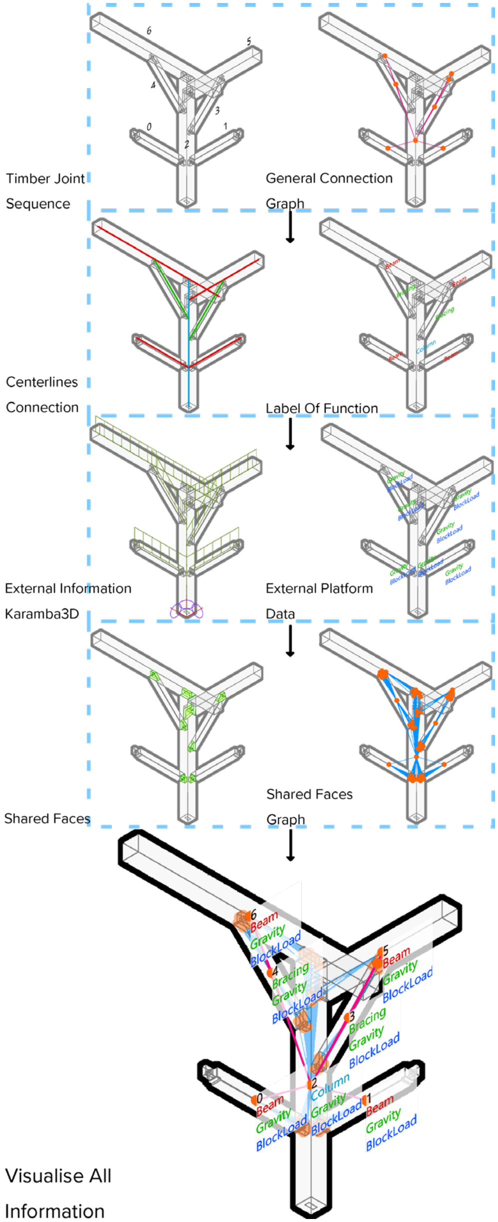
Topological Extraction System Approach

The joint connections were sorted according to the Z-coordinate values of each component, which is essential information while assembling the timber frame structure. Topologic was applied to extract and visualise the relationship between the elements within the imported models, and the relationship of shared faces among components was visualised (Figure 4).

Figure 4 (LHS)
Graph representation of the selected joints

Figure 5 (RHS)
System structure





Knowledge Graph Exploration

Building on this foundation, external simulation results from Karamba3D were also imported into Topologic to maximise the graph's dictionaries. In Figure 5, showcasing the structure of the following four aspects of informational levels: 1) General topological relationships: the script first organised the order of the components. 2.) Centreline connection: Then, it analyses and shows the connection between the components. Moreover, the centroid points from timber joint components were extracted, and a centreline connection was created to identify the function of the component: Beam, Column, and Bracing components; 3.) External simulation: Karamba3D was used to analyse the load distributions across the structure. These data were imported into the graph's dictionary; 4.) Logic relationship of connections: analysing shared faces within the joints to understand the function surfaces better. The output data from Topologic is structured in a multi-layer: 1.) The sequence of components; 2.) Function of components; 3 and 4.) Type of loads being applied to the imported structure. This information contributes to developing a deeper comprehension of the knowledge graph.

Generative Design Experiment: Rule-Based Generative System

This section aims to experiment with various conceptual relationships within timber frames. The external plug-in WASP was used to generate new approaches to the design. This experiment developed the method using three connection types - beams, columns, and braces. These generated models were then integrated into the proposed topological system for topological analysis and to extract the relationship of structures. The generated structures show that the proposed graph extraction system can be applied to analyse complex timber frame combinations (Figure 6).

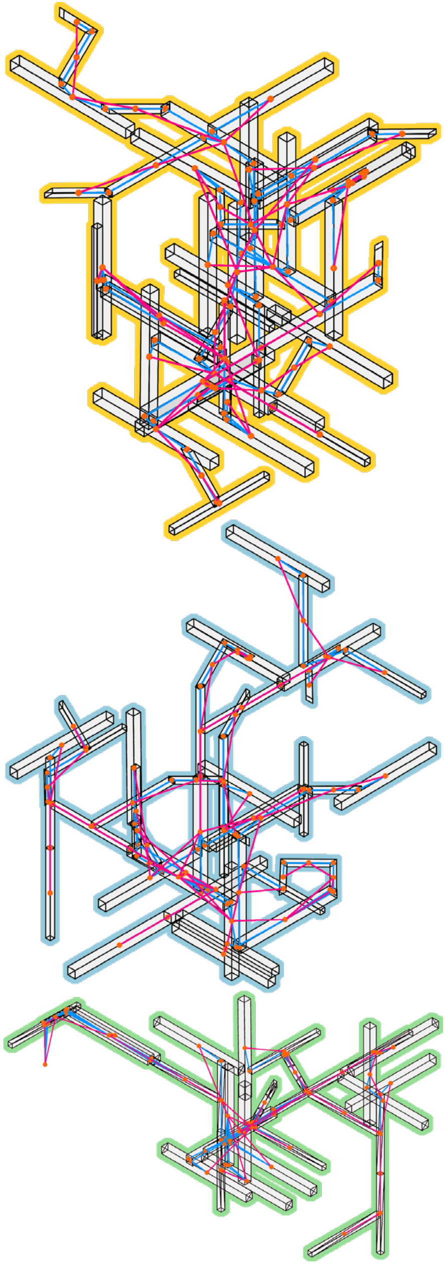


Figure 6
3 structures
generated using
WASP

DISCUSSION & FUTURE DEVELOPMENT

This study has developed a prototype system for knowledge graph extraction using Grasshopper, Topologic, and Karamba3D. The proposed approach not only enables the analysis of spatial relationships between the imported models but also supports the integration of external data. By implementing various information into the system, which is able to create a multi-layered data structure, a potential framework to develop a knowledge graph extraction system in a visual programming language environment. Moreover, the integration of a knowledge graph shows the potential of machine learning applications in architectural design. By translating 3D modelling, such as timber joint connections, into a machine-readable language through the application of graph-based theory.

In order to ensure the foundation of the timber joint connections graph for future application of machine learning, the database needed to contain a high structural standard, including detailed structural analysis and simulation of timber joints. This structural layer of information is critical for validating the mechanical performance of the joints, especially with rule-based applications. With the application of a rule-based generative approach, such as shape grammar, the framework can be extended to maximise the synthetic database. However, the performance-based validation will be critical to ensure the generated joints meet the structural standard for building codes. This step is not only essential to improve the future framework of generation-to-fabrication, but also to ensure the training of machine learning algorithms is based on verifiable structural performance.

Furthermore, this study opens up future research directions beyond timber joint design and application. The methodology of translating 3D models into a graph-based representation and knowledge graph is not only able to analyse and generate timber joint designs but also establishes a potential framework for applying to various architectural design applications. This includes the integration of Graph Neural Networks (GNNs) in developing an architectural design prediction assistant and optimisation, which is able to handle multidimensional information. The development of digital twins involves a knowledge graph that helps to store various layers of building information and links data between physical and virtual systems. Building Topology Ontology (Rasmussen, 2020) linking Building Data Group, achieving semantic interoperability between building blocks, systems, and data platforms.

CONCLUSION

In this research, we presented an early-stage knowledge graph extraction approach developed in Grasshopper. This approach aims to expand the data structure from a general graph analysis into a comprehensive knowledge graph. We presented the graph extraction system approach and showcased the results generated from the script. The proposed system is able to capture different levels of informational layers, including components' relationships, import external data, and shared faces relationships.

The principle of timber joint connections utilises simple geometric shapes to interlock multiple components into a structure. Shared faces are one of the key aspects of the connection. With the application of Topologic, the proposed system proficiently analyses and extracts information on shared faces, enhancing our understanding of timber joint mechanics.

Furthermore, this study explored the implementation of external information into the graph. Karamba3D was applied in this study to demonstrate the process of expanding the graph's data repository. The system included developing a sorting system aligned with the Z-axis. Followed by the selected model in Karamba3D for load analysis. The result was then imported into the graph's dictionary, creating a knowledge graph with a multi-layered data structure.

Then, visualising the relationship among the joints was generated. The result shows that the graph visualises both information from Topologic and Karamba3D. The topological system focused primarily on preparing the foundation for creating a more informative graph without deeply exploring the specific details of wood joints.

In order to maximise the potential of the application in constructing a knowledge graph of the structural connection, further structural analysis needs to be implemented. Integrating finite element analysis will be crucial for developing the structural knowledge of the joints. Including stress analysis, deformation analysis, etc., which helps deepen the graph's informational level.

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