EXPLORING RULE-BASED DISCRETE TIMBER DESIGN WITH MORTISE-TENON JOINTS

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Abstract. Digitisation in timber-frame architecture offers potentials to revitalise traditional building methods within a contemporary setting. This paper explores an automated design workflow for creating digital timber frame systems, incorporating mortise-tenon joints (MTJs) and principles from traditional Chinese architecture, including Dougong brackets and rural housing. The novelty resides in developing a comprehensive digital library of MTJs in the form of discrete timber blocks, which in return, facilitates the design of adaptable and reconfigurable timber housing. Addressing the classification and algorithmic reproduction of MTJs, the study introduces a methodology for rule-based generative design, which includes the identification of principles governing joint interlocking, automated joint generation, and block combination and aggregation. The approach includes analysing traditional timber jointing types, parameters, and constraints, followed by coding a MTJ library and combinatorial patterns for assembling discrete timber blocks. The resultant discrete timber forms, informed by Dougong's compositional rules and patterns observed in rural timber housing, present the possibility of extendibility and reconfiguration. This research culminates in a digital toolset that enables the fusion of time-honoured MTJs with contemporary computational design, aiming to extend the capabilities of traditional timber frames.

Keywords. Mortise-Tenon Joints, Discrete Timber Blocks, Digital Timber Frame, Combinatorial Design, Rule-Based Generative Design

1. Introduction

As the industry endeavours to diminish the impact of embodied carbon and ultimately pursue a more sustainable built environment future, timber building has gained growing attention as a green alternative to conventional concrete and steel (Reyes et al., 2021). Computational design tools and mass timber construction have been employed to explore innovative formal possibilities of intricate, flexible, and adaptable timber architectures (Retsin, 2019b). This approach thus holds the potential to

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revolutionise timber structure systems by employing mortise-tenon joints (MTJs) as the primary connection method in traditional housing designs (Qiao et al., 2021).

Historically, the study of the mortise-tenon principle in Chinese timber frame architecture dates back to the ancient Song dynasty. Li Jie authored the Yingzao Fashi (1103), establishing a Cai-fen modular system for timber frames with MTJs (Liang, 1803). Based on Yingzao Fashi, MTJ principles have been investigated in generative design in a limited number of previous studies. Traditional Chinese timber frames and their Dougong brackets were studied by applying the concept of shape grammars and creating a set of rule-based grammars for generating their forms (A. Li, 2001; Wu, 2003). These shape grammars suggested an extension of Yingzao Fashi to the computational field; however, they have not been used to generate innovative designs.

Recent studies highlight the discrete design strategy's potential for innovative timber architectures, using modular blocks numerically understood (Retsin, 2019b). While Retsin's Tallinn Pavilion 2017 and Royal Academy Installation 2019 show this strategy's creative applications, they face reconfigurability limitations due to threaded rod connections. Conversely, MTJs offer interlocking, flexible, and reversible connections, allowing for reducing these restrictions. In the latest studies, Dougong components have been simplified and applied to parametric design (Zhao et al., 2021), but these studies have primarily focused on digital fabrication rather than emphasizing a patterned and replicable design process. Moreover, with the computational analysis of the topological system of the Dougong, the logic of its composition has been developed (Lin & Hou, 2022). While it has generated new types of Dougong design, its capability to generate architectural scale projects remains limited, and the comprehensive investigation of the intricacies of MTJs has yet to be thoroughly undertaken. In order to fill part of this knowledge gap, this paper seeks to propose a novel digital design method that combines computational logic with MTJs to facilitate their effective application in contemporary houses.

Based on the above state-of-art, this research aims to address the complexities and limitations of traditional MTJ systems inherent in the context of digital design transformation. Therefore, to simplify traditional MTJ while maintaining its advantages and to break through the limitations of traditional timber applications in contemporary houses, this research proposes a spatial combination design method based on the geometry and connection logic of traditional Chinese MTJs. This approach transforms MTJs into a shape library in the form of discrete blocks, digitally redefining the shapes and joining patterns of MTJs. Additionally, it develops geometric and spatial connection rules for combinatorial design to enable aggregation, which together with the shape library results in a workflow for flexible timber forms design.

2. Framework and Methods

The research framework is grounded in the principles outlined in our previous work (Xu et al., 2023). Leveraging a rule-based generative approach for a flexible timber design system, this framework consists of three parts: first, developing modular systems for MTJs based on Yingzao Fashi; second, exploring discrete strategies for timber block combinatorics; and third, merging these strategies with shape grammar for MTJ-based discrete timber design. This framework attempts to adapt traditional Chinese timber frame techniques, utilising MTJs in contemporary contexts, thereby developing a digital approach for flexible timber design.

Following the foundational framework, the methods employed in this study provide an in-depth exploration of the principles and modularity of MTJs and rule-based discrete timber design. The paper integrates the algorithmic logic for more complex and varied design iterations based on the establishment of MTJs libraries, along with the Grasshopper Python component developed as a design tool. The focus lies on exploring the combinatorics of discrete blocks and integrating shape rules for more customisable and reconfigurable aggregations of timber forms. These methods systematically reinterpret traditional principles through digital tools, intending to combine historical craftsmanship with contemporary architectural needs.

3. Discrete Mortise-Tenon Timber Design Workflow

This paper proposes a design workflow for discrete timber blocks incorporating MTJs, delineating a comprehensive methodology from the development of an MTJ library to the aggregation of timber forms, as shown in Figure 1. This systematic workflow begins with the identification of traditional MTJs in order to establish a digital foundation. The focus then shifted to exploring the computational attributes of discrete timber blocks suitable for MTJs, emphasising that the combination of blocks adheres to MTJ principles. The third phase integrates the data on various MTJ types and block combinations to automatically generate available MTJ geometries. The final phase extends the block combinations base and incorporates rules extracted from traditional Chinese timber frames to enable the aggregation of timber forms. These forms are then applied in generating MTJ geometries and visualising assembly sequences.

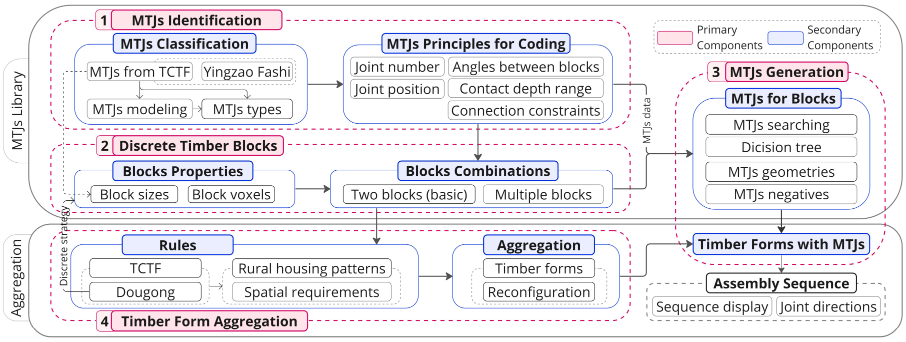


Figure 1. Overall workflow from MTJs library to aggregation of timber forms (figure by author)

3.1. MORTISE-TENON JOINTS IDENTIFICATION

The identification of MTJs forms the foundation of this study, which involves the classification of traditional joints and their subsequent encoding for digital manipulation. This process aims to create a shape library and establish coding principles that are essential for the innovative design and assembly of timber structures. Subsequent analyses will expand on these classifications and principles, bridging historical timber craftsmanship with computational design.

MTJs achieve interlocking through imposition of geometric constraints, enabling reversible connections. In traditional Chinese timber frames (TCTF), various MTJ types can be identified by analysing different connection positions of timber elements. Figure 2a illustrates five basic MTJ types with 0- or 90-degree angles, which support the assembly of straight-shape, L-shape, T-shape, and X-shape for specific joining needs. Additionally, there are three other MTJ types with non-0 or non-90-degree angles allow for connections between horizontal and oblique members, such as beams and cantilevers in TCTF. Different connection positions impact the geometric contact volume that must be subtracted from timber blocks to create concavity or convexity.

Based on these classifications, this paper creates a shape library of MTJs containing the MTJs' geometry for connection logic in the x, y, and z axes. Figure 2b shows the matrix of these shapes records the three-dimensional connection directions for each specific MTJ, corresponding to the axis of the spatial relations between discrete timber blocks for combinatorial design in a later stage. Moreover, these spatial relations determine the suitable MTJs that fulfil the requisites of the jointing sequence and spatial geometric constraints to ensure stable mechanics in the connection.

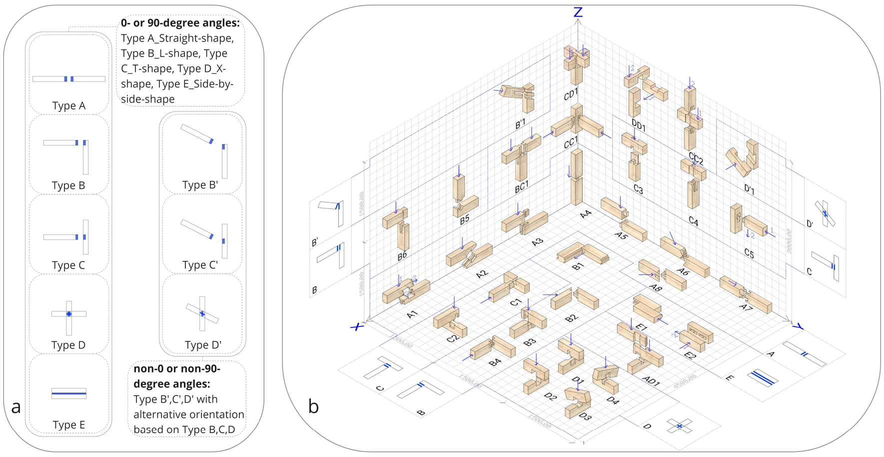


Figure 2. a: MTJs types based on connection positions and angles, b: MTJ shape library with the geometries and connection directions of are sorted on the x, y, and z axes (figure by author)

To facilitate the application of classified MTJs in subsequent discrete design processes and automated generation of joint geometries, this paper converts MTJ shapes into a database equipped with parametric variables. Figure 3 illustrates the data transformation for a selection of MTJ shapes from the shape library shown in Figure 2b, with the approach maintained for other MTJs to systematically establish parametric variables. Different MTJs are distinguished by MTJ types and numbers. For instance, Type A is assigned '0' as the path number, and the first MTJ of Type A is given '0' as the item number; hence, MTJ A1 is encoded as (0,0) for the identification and retrieval of corresponding MTJ parameters during computational processes. The second critical parameter is joint position, identified by marking the contact position on the top, end, or side surfaces of two timber blocks, which will be encoded for computational correspondence in the next step of discrete block combinations. In this paper, angles between blocks are primarily 0 or 90 degrees, but additional angles are also developed and explored for more complex designs. The contact volume range usually includes the whole or half in traditional MTJs, but in this design system, this parameter varies within a range depending on the density or stability required by the stacking blocks. The final parameter documents the geometric or gravity constraints of MTJs on the X, Y, and Z axes, potentially utilised to assess structural performance and the sequence of connection directions. This MTJ data will expand with the refinement of the MTJ shape library to meet specific design requirements.

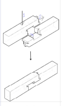
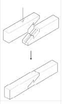
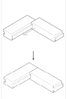
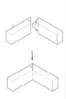
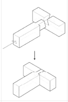
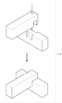
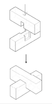
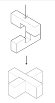
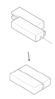
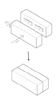
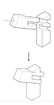
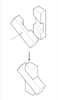
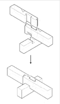
MTJs Schematic Diagram			..			..			..			..			..			..		..
MTJs Number	A1 (0,0)	A2 (0,1)	..	B1 (1,0)	B2 (1,1)	..	C1 (2,0)	C2 (2,1)	..	D1 (3,0)	D2 (3,1)	..	E1 (4,0)	E2 (4,1)	..	B'1 (5,0)	D'1 (7,0)	..	AD1 (8,0)	..
MTJs Types	Type A_Straight-shape	Type A_Straight-shape	..	Type B_L-shape	Type B_L-shape	..	Type C_T-shape	Type C_T-shape	..	Type D_X-shape	Type D_X-shape	..	Type E_Side-by-side-shape	Type E_Side-by-side-shape	..	Type B'_L'-shape	Type D'_X'-shape	..	Type A_Straight-shape, Type C_T-shape	..
Joint Position	End-End	End-End	..	End-End_side	End-End	..	End-Side	Top-Top	..	Top-Top	Top-Top	..	Side-Side	Side-Side	..	End-Top	Side-Side	..	End-End, End-Top	..
Angles between Blocks	0°	0°	..	90°	90°	..	90°	90°	..	90°	90°	..	0°	0°	..	others	others	..	0°, 90°	..
Contact Volume Range	Whole	Whole	..	Edge	Whole	..	Whole	Half	..	Half	Whole	..	Edge	Edge	..	Whole	Whole	..	Half, Whole	..
Constraints in Axes	X, Y, Z (Geometry & Gravity Constrains)	X, Y, Z (Geometry & Gravity Constrains)	..	Y, Z (Geometry Constrains)	Z (Geometry Constrains)	..	Y, Z (Geometry Constrains)	X, Y, Z (Gravity Constrains)	..	X, Y, Z (Gravity Constrains)	X, Y, Z (Gravity Constrains)	..	X, Z (Geometry Constrains)	X, Z (Geometry Constrains)	..	X, Y, Z (Geometry Constrains)	Y, Z (Gravity Constrains)	..	X, Y, Z (Geometry & Gravity Constrains)	..

Figure 3. Parameter variables for the transformation of partial MTJs from shapes to data (figure by author)

3.2. DISCRETE TIMBER BLOCKS

The concept of part-to-whole in discrete architecture comes from mereology, which involves utilising a limited set of parts to consist of a whole design (Koehler, 2018; Retsin, 2019a). This strategy goes beyond conventional modular design and facilitate the digital manipulation of MTJs in the form of discrete timber blocks. This section explores how encoded timber blocks, related to Dougong and MTJs and adhering to various combinatorial rules, offer the potential to reconfigure spatial patterns.

The Dougong in TCTF exemplifies a highly modular design, achieving outstanding structural stability and aesthetics through the connection of MTJs stacked up layer by layer. Incorporating the discrete approach, the Dougong form is adaptable to flexible timber architecture through discrete blocks. As illustrated in Figure 4a, a section of the Dougong bracket on the left has three tiers with three different lengths of timber, and each horizontal bracket bay is 300 mm according to the 8th-grade timber in Yingzao Fashi. The discrete form of Dougong utilises all timber blocks with the basic size, including cross-section dimensions of 150mm x 100mm and length of 700 mm (the minimum Gong block length from Dougong). The block length is determined by the number of bays and accounts for the subtractive volume required for the MTJs of timber blocks. Additionally, an extra 50mm is allocated to both ends of the block to accommodate the overlapping part. Hence, the block length is calculated by the number of bays x 300mm + 2 x 50mm as shown in Figure 4b. Block lengths of 1300mm and 400mm are also considered for the efficiency and flexibility of combinatorial design. To enable the recognition of relative connection positions of discrete blocks combined with MTJs data, encoded voxels of identical sizes are generated, reflecting the properties of the blocks. As shown in Figure 4c, the sequencing of voxel generation within each block begins at the centre and incrementally extends towards the edges. The numbers assigned to voxels facilitate the matching of with connection relations of various MTJ types during block combinations and MTJ geometries generation.

Combinatorial designs are derived from permutations and combinations of discrete parts (Sanchez, 2016). In the context of discrete timber with MTJs, this involves the application of algorithms based on shape grammars that consider spatial relations such as joint position, angles, and contact volume range. These algorithms correspond to a comprehensive MTJ database, setting the foundation for the specific style of design. Based on this, the paper introduces a custom component for block combinations developed in Grasshopper Python, which operates by employing the types of MTJs as conditions to calculate all combinatorial possibilities and to invoke other MTJs data under that type for spatial operations. As shown in Figure 4d, the primary combinatorial logic translates the spatial relations between blocks for each type of MTJ into relative positions and angles between voxels within the blocks. This is followed by the duplication, rotation, and movement of the initial block to generate and iterate blocks for combination. Taking MTJs Type D as an example, its characteristic connection position at the non-terminal intersection of blocks is interpreted as excluding both ends n and n-1 of the voxels in a block. Thus, the reference voxels for combinatorial arrangements are from voxel 0 to n-2 of the initial block and from voxel 0 to n-2 of the iterative block. Once the list of voxel combinations is obtained, the voxel centre of each iterative block serves as the starting point for movement, with the corresponding voxel centre of the original block as the target point. Additionally, adjustments to various angles and contact volume ranges can be made as required.

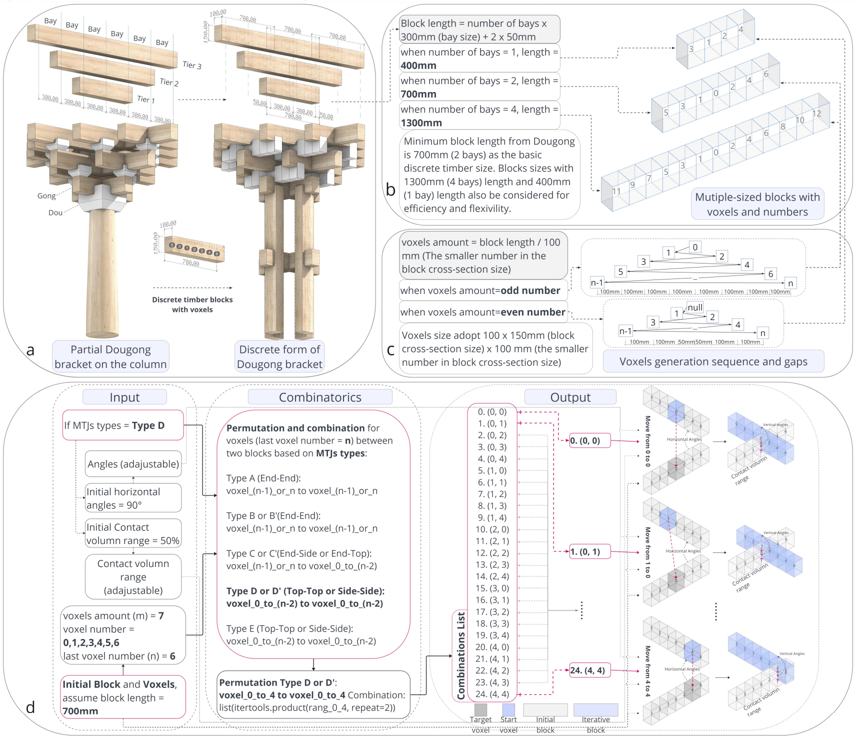


Figure 4. a: Discretization of Dougong by discrete timber blocks with voxels, b: Timber blocks size calculations, c: Voxels generation and sizes, d: Combinatorial Logic of Discrete Timber Blocks linking MTJs types and combination graphs in MTJs Type D as an example (figure by author)

3.3. MORTISE-TENON JOINTS GENERATION

The automated generation of MTJs geometry is based on integrating MTJs data and discrete blocks combinatorics, both derived from the previous two phases. It begins with searching for available MTJ types of intersecting blocks and then proceeds to generate geometries based on the matched MTJs. This process allows to generation of suitable MTJs for discrete timber architecture forms with various block combinations.

A critical prerequisite for generating MTJ geometries is the systematic search for potential MTJ types, crucial for precisely aligning the discrete block combinations. This phase is pivotal as it sets the foundation for the subsequent generation of joint geometries. It requires a methodical classification of intersecting block types, their spatial relations, and possible interlocking patterns. Following this classification, the method for identifying suitable MTJ types for discrete blocks, demonstrated in Figure 5, employs computational representation. This includes categorising contact voxel relations and applying vector mathematics to define block interactions. In terms of voxel relations, the ranges used to filter the voxel contacts between two blocks are synchronized with the list of block combinations to initially determine MTJ types. On this basis, the parallel, orthogonal, or other properties of the block interactions are determined by evaluating the vector cross-products and dot-products, ultimately leading to a match with the available MTJ types. This establishes a clear protocol for identifying various MTJ configurations ranging from simple linear connections to complex intersecting forms. This structured approach ensures that the geometry generation process is both efficient and precise, allowing for the seamless integration of MTJs into the diverse array of timber forms.

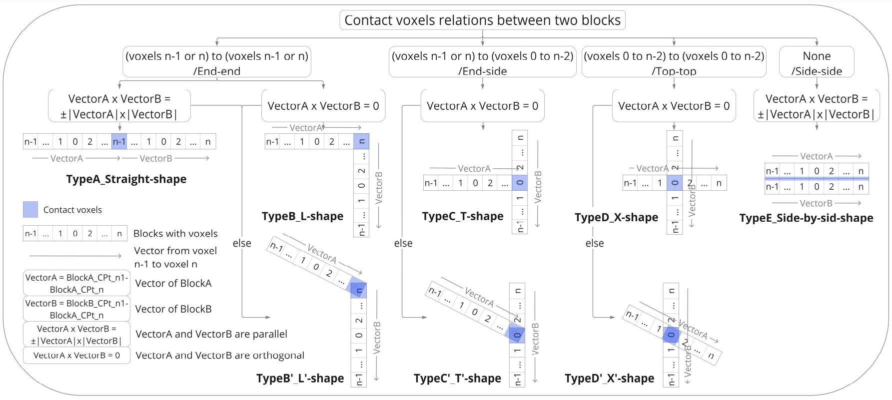


Figure 5. Searching method of identifying available MTJs types for discrete blocks (figure by author)

The proposed automated generation of MTJs relies on the underlying logic based on the principles of MTJs. The whole process commences with the input of discrete timber forms to extract the combinational scenarios for each block. It then proceeds to search for available MTJs within the defined spatial relations, culminating in the algorithmic and spatial manipulation to generate the MTJ geometries. As highlighted in Figure 6, the method initiates by calling the geometric properties of the block and voxel from the combination scenario to obtain the intersecting volume of the blocks and the voxel centroid, which is then used to calculate a plane to split the intersection to get two MTJ negatives. Subtractive operations are subsequently applied to the blocks to generate blocks incorporating MTJs. Owing to its reliance on block volumes and cutting planes calculated from voxels, this method remains applicable for generating MTJs in combinatorial scenarios with varying angles or contact volume parameters.

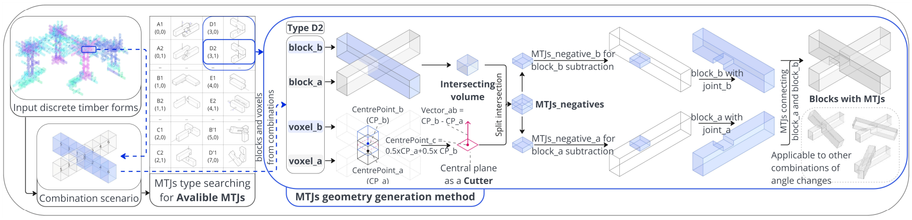


Figure 6. MTJs generation process highlighting generating Type D2 geometries (figure by author)

3.4. TIMBER FORM AGGREGATION

The aggregation of discrete timber forms represents a further exploration of the fundamental combinatorial principles associated with discrete blocks, alongside the Dougong and TCTF rules, to generate coherent patterns by composing architectural elements to the whole timber framing form. Before aggregating to the timber form, it is essential to determine the architectural elements that aligned along horizontal and vertical orientations. The generation of these elements is guided by rules that stem from the topological relations inherent in the highly modular Dougong system. Based on the previously acquired discrete form of Dougong, which exhibits the potential to stack upwards with increasing tiers and extend horizontally, Figure 7a demonstrates the rules of the Dougong pattern. These rules are formulated by encoding the sequential aggregation of discrete blocks in ascending order and connecting the intersections of block pairs using the spatial relations defined in the fundamental combinatorial principles. Additionally, to enhance the efficiency of vertical aggregation, a set of rules for the column pattern has been established, based on the spatial relations between the lowermost horizontal blocks of the Dougong, integrated with vertical blocks as shown in Figure 7b. This allows linking Dougong and column patterns to obtain beam-column-like timber architectural elements, as Figure 7c shows, which also provides the potential for the extension or replacement of discrete blocks for reconfiguration.

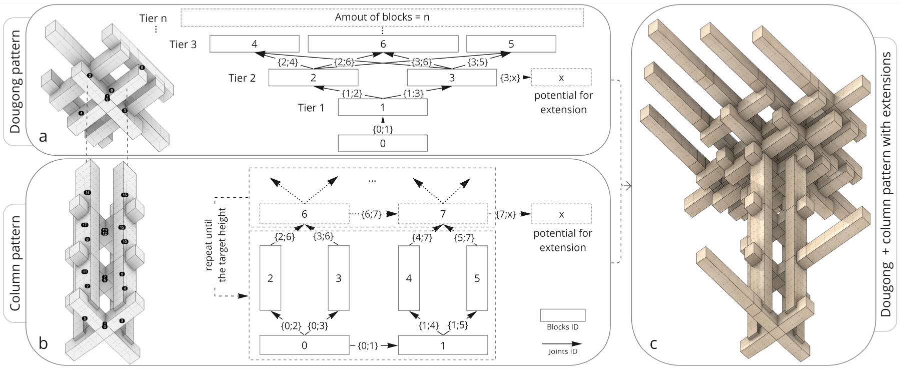


Figure 7. Rules for Dougong-based discrete architectural elements generation (figure by author)

Beyond the scale of the architectural elements, a more comprehensive hierarchy of principles, grounded in Dougong rules, is required to govern the starting, connecting and ending points for timber form aggregations. As an approach for developing these principles and as a platform for testing the proposed design strategy, the aggregation rules are derived from both TCFT and rural housing patterns in China. Typically, rural timber houses feature rooms enclosing various types of courtyards, such as open, three-sided, and four-sided courtyards, as illustrated in Figure 8a. The variation in courtyard patterns can be parametrically interpreted from the relative positioning of rooms in a plan, providing layout outlines for planar generation of timber forms. Moreover, the inflection points of these outlines serve as starting points for upward aggregation in the column pattern. Additionally, a key observation of TCTF is the similarity of Tailiang frame's generation logic to the tiered upward progression dictated by Dougong rules, progressively narrowing towards the apex, as shown in Figure 8b. By extracting this stepwise upward rule, the height of each Dougong pattern aggregation and the extent of its horizontal extension are constrained. This approach shapes the discrete timber frame form, as demonstrated in Figure 8c, integrating the structural logic of traditional rural architecture with contemporary computational design techniques.

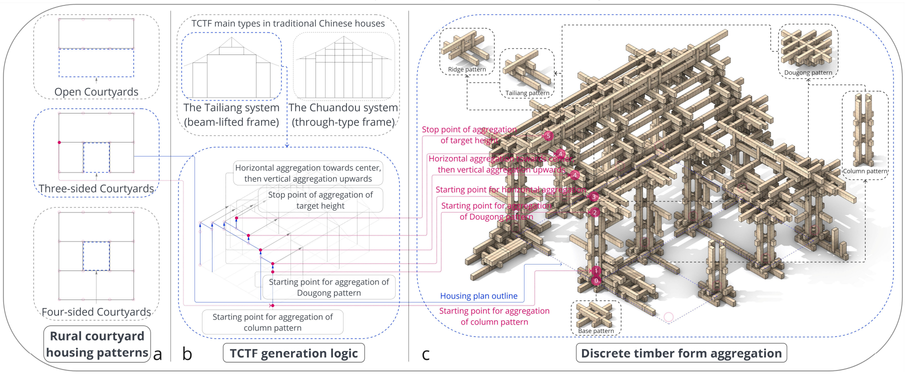


Figure 8. Timber framing logic for discrete timber form aggregation (figure by author)

4. Results

This research innovatively integrates traditional MTJs with digital design, developing a comprehensive method for the design of timber frame architecture. Moving beyond previous studies primarily focused on digital fabrication or aesthetics, this study introduces a detailed and systematic approach that emphasises the utilisation of MTJs to augment digital timber design. The methodology encompasses the identification, digitisation, and application of MTJs in a combinatorial design process, specifically aimed at investigating their functional and structural potential within digital timber architecture. The creation of a digital MTJ library, featuring diverse joint types classified by their geometric and interlocking properties, establishes a versatile foundation for designing adaptable timber forms. This method creates a solution that combines traditional craftsmanship with contemporary design principles to preserve traditional aesthetics while facilitating the automated generation of timber structures. However, the wider application of this approach is potentially constrained by the computational complexity involved in generating and assembling discrete timber blocks, in addition to the requisite further alignment and refinement between computational design methodologies and traditional joinery practices.

5. Conclusion

This research contributes to the development of digital timber architecture through merging traditional mortise-tenon techniques with contemporary computational design strategies. The innovative design approach, developing from the establishment of a digital MTJ library coupled with a rule-based discrete timber design workflow, is inspired by traditional Chinese architectural techniques yet extended through digital technology and design thinking. This approach facilitates novel explorations into adaptability and reconfigurability of contemporary architectural forms. Nevertheless, the transition of traditional joinery into a digital design context and the complexity inherent in the computational processes for multiple combinations of discrete timber blocks present challenges that require further investigation. Overall, this research bridges the gap between traditional MTJs and digital innovations, opening up possibilities for flexible timber architectural design. Additionally, while the system exhibits considerable customisability, further research should focus on refining computational strategies and assessing the scalability and practical applicability of this approach, particularly in the context of rural timber housing.

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