buildings

MDPI

Article

Preserving Woodcraft in the Digital Age: A Meta-Model-Based Robotic Approach for Sustainable Timber Construction

Zhe Lai [1,2], Yingying Xiao [3], Zitong Chen [4], Huiwen Li [5] and Lukui Huang [6,*]

[1] School of Architecture, South China University of Technology, Guangzhou 510641, China; zhelai4-c@my.cityu.edu.hk
[2] Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong 999077, China
[3] Tongji Architectural Design (Group) Co., Ltd., Shanghai 200092, China; xiaoyingying@tjad.cn
[4] College of Architecture and Planning, Fujian University of Technology, Fuzhou 350118, China; 15626147982@163.com
[5] College of Urban and Rural Construction, Zhongkai University of Agriculture and Engineering, Guangzhou 510641, China; mowhite1222@163.com
[6] School of Accounting and Auditing & Guangxi Key Laboratory of Seaward Economic Intelligent System Analysis and Decision-Making, Guangxi University of Finance and Economics, Nanning 530031, China
* Correspondence: lukui-hua59@tbs.tu.ac.th

Abstract: This study presents an innovative approach to sustainable timber construction by integrating traditional woodworking techniques with advanced robotic technology. The research focuses on three key objectives: preserving traditional craftsmanship, enhancing material conservation, and improving production efficiency. A meta-model-based framework is developed to capture the woodcrafts of mortise and tenon joints, which are prevalent in traditional Chinese wooden architecture. The study employs parametric design and robotic arm technology to digitize and automate the production process, resulting in significant improvements in material utilization and processing efficiency. Specifically, this study utilizes genetic algorithm strategies to resolve the problem of complex mortise and tenon craftsmanship optimization for robotic arms. Compared to conventional CNC machining, the proposed method demonstrates superior performance in path optimization, reduced material waste, and faster production times. The research contributes to the field of sustainable architecture by offering a novel solution that balances the preservation of cultural heritage with modern construction demands. This approach not only ensures the continuity of traditional woodworking skills but also addresses contemporary challenges in sustainable building practices, paving the way for more environmentally friendly and efficient timber construction methods.

Keywords: robotic arms; woodcraft; tenon and mortise joints; meta-model

check for updates

Citation: Lai, Z.; Xiao, Y.; Chen, Z.; Li, H.; Huang, L. Preserving Woodcraft in the Digital Age: A Meta-Model-Based Robotic Approach for Sustainable Timber Construction. *Buildings* **2024**, *14*, 2900. https://doi.org/10.3390/buildings14092900

Academic Editor: Binsheng (Ben) Zhang

Received: 11 July 2024
Revised: 31 August 2024
Accepted: 4 September 2024
Published: 13 September 2024

1. Introduction

Wood is widely recognized as a highly sustainable construction material due to its renewability, carbon sequestration capabilities, and superior environmental performance [1,2]. Advancements in wood formation research in recent years have led to the creation of various wood composite products that offer enhanced stability and predictability [3]. Modern engineered wood has become one of the most promising and valuable construction resources for the future [4]. By preserving wood's inherent qualities — such as its light weight, workability, and organic texture—these innovative techniques have effectively addressed natural wood's deficiencies, including knots, cracks, and susceptibility to corrosion.

Many traditional dwellings worldwide, especially in China, are timber-structured and serve as irreplaceable cultural artifacts that reflect the architectural ingenuity, craftsmanship, and cultural heritage of past generations. Woodworking techniques are intrinsically linked to the preservation of traditional dwellings. The manual nature of these methods often results in extended project timelines, affecting both the efficiency and scalability of construction projects. The declining number of skilled carpenters has further escalated the costs associated with timber construction, making traditional timber framing increasingly challenging in today's fast-paced, cost-driven construction industry. Although modern CNC systems and machines have been widely used to improve efficiency, they often struggle with the necessary precision and minimized waste that skilled human hands can accomplish. Additionally, to reduce costs, traditional mortise and tenon joints, which are typical in timber framing, are often replaced by more cost-effective steel components and bolts. From the perspective of cultural heritage preservation, this shift poses a significant challenge, as it compromises the authenticity and integrity of traditional craftsmanship and construction techniques. Thus, this study seeks to address these issues with robotic arms.

The integration of robotic systems into modern construction has significantly enhanced production efficiency [5–8]. In the past few decades, robotic construction research has gained increasing attention [9–11]. Research institutions such as the Institute for Computational Design (ICD) in Stuttgart, Germany [12]; the Swiss Federal Institute of Technology (ETH) in Zurich, Switzerland [13,14]; and the Laboratory for Timber Constructions (IBOIS) at the Swiss Federal Institute of Technology (EPFL) [15] have integrated factors such as material systems, performance parameters, processing limitations, and construction tools to establish a relatively mature set of theories and methods for architectural robotics research. In practice, the adoption of robots in the construction industry addresses many of the challenges associated with manual labor, such as labor shortages, inconsistencies in craftsmanship, and the slow pace of traditional methods. Although traditional CNC machining for wood processing improves precision and efficiency, it still requires substantial manual intervention [16], especially in the manufacturing of complex structures [17]. Additionally, the programming and debugging time for CNC machines is comparatively lengthy [18–20]. In contrast, robotic solutions employing advanced algorithms enable complex designs and unique architectural requirements, making them highly versatile and efficient tools for modern construction projects [21–23].

The use of robots in timber construction not only improves efficiency but also contributes significantly to sustainability by reducing material waste [24–26]. Traditional construction methods often result in considerable wood waste due to human error and the limitations of manual tools. CNC machines have also been criticized for material utilization and waste management [18]. However, robotic systems, equipped with precise cutting and milling technologies, can optimize the use of raw materials by minimizing offcuts and ensuring accurate measurements. Research has shown that robotic fabrication processes can achieve higher material yield and less waste generation, aligning with sustainable building practices. Research has shown that robotic fabrication processes achieve higher material yields and generate less waste, aligning with sustainable building practices. Additionally, these systems can be programmed to use digital design models to maximize resource utilization [26], further enhancing the sustainability of construction projects.

The application of robotics in the preservation and innovation of traditional woodworking techniques is an emerging area of research [27–30]. The application of industrial robots in timber building production has not only advanced traditional woodworking processes such as measuring and marking, lumber preparation, and joinery but has also expanded into new areas of timber construction through precise positioning and installation. These technologies also facilitate the restoration of aging wooden structures, preserving cultural artifacts that might otherwise be lost [27].

In this study, we examine Bai traditional dwellings in China's Dali area, which is known for its distinctive architectural styles and skilled craftsmanship. By focusing on the Bai ethnic woodworking techniques, particularly mortise and tenon joints, we illustrate how advanced digital technologies can be used to preserve traditional woodworking methods and, by extension, traditional dwellings in a more efficient and sustainable way.

Focusing on mortise and tenon joints offers several significant advantages. First, the design of mortise and tenon joints is highly standardized, making them suitable for large-scale production while requiring minimal specialized tools. This standardization aligns with modern production needs and can easily be adapted for use with robotic systems. Second, mortise and tenon connections can be replaced without compromising the building's overall integrity. In the case of severe damage, entire structures can be disassembled and repaired. Moreover, mortise and tenon provide superior earthquake resistance compared to nails or other metal fasteners [31]. The Bai region is seismically active. The joints in traditional timber structures can effectively absorb and dissipate seismic energy. This not only underscores their environmental and cultural significance but also highlights their practical utility in seismically active areas.

This research proposes a meta-model that captures the essence of their woodworking techniques regarding tenon and mortise joints. A meta-model is a high-level framework that describes the structure, relationships, and properties of models within a specific domain. In the context of this research, the meta-model serves as an abstract representation of traditional woodworking techniques, particularly for mortise and tenon joints in Chinese wooden architecture. A meta-model-based automotive approach to reproducing complex mortise and tenon joints through the Grasshopper platform and the KUKA PRC plugin using robotic arms is proposed and examined (Figure 1). Grasshopper, a graphical programming interface for Rhinoceros software (Version 8), enables complex calculations and operations on design models. The KUKA PRC plugin, developed for Grasshopper, facilitates robot execution code generation and cross-platform simulation, providing robust technical support and algorithmic foundations for robotic processing. This integrated approach offers a powerful method for preserving and replicating traditional woodworking techniques using advanced robotic technologies.

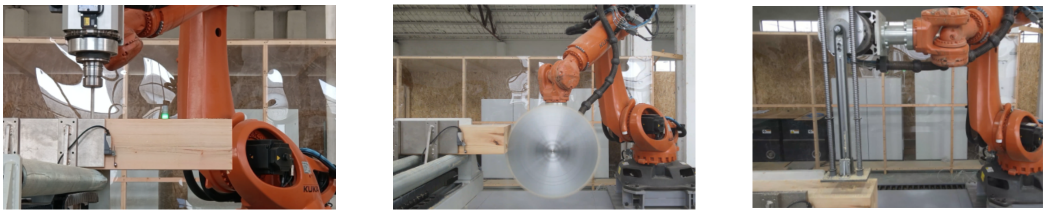


Figure 1. The proposed robotic timber construction process.

Research Contribution

This study aims to address three core issues in robotic applications in timber construction: the preservation of traditional woodworking techniques, the improvement of production efficiency, and the control of material waste. We propose a robotic timber fabrication strategy for mortise and tenon joints based on a meta-model, as illustrated in Figure 2.

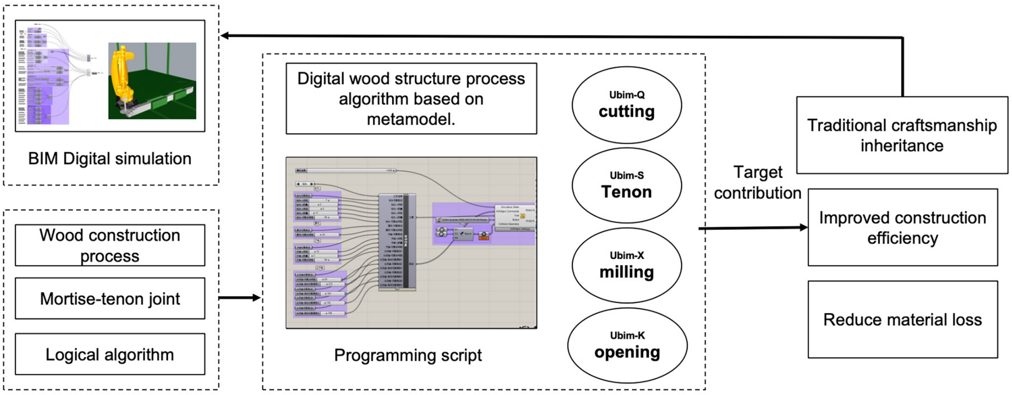


Figure 2. Digital construction process of woodcraft based on a meta-model.

The main contributions of this study are shown as follows:

Firstly, this study conducts a comprehensive investigation into the mortise-tenon structures and woodworking tools utilized in traditional timber buildings in the Jianchuan area of Dali, China. It contributes to the research in applying construction robotics to traditional architectural craftsmanship. Moreover, it explores the integration of robotic arms to standardize the fabrication of basic structural elements—mortises and tenons—in traditional Bai ethnic architecture. This integration aims to enhance the consistency and precision of timber component shapes during automated processing while preserving and advancing the essence of traditional craftsmanship.

Secondly, this study examines traditional residential woodworking techniques from the perspective of preserving intangible cultural heritage. It proposes an innovative strategy for digital inheritance that merges these techniques with modern digital architectural science. By using digital technologies, the study aims to address challenges in preserving woodworking skills and promote their application and transmission in contemporary architecture.

Thirdly, the study introduces an automated processing strategy that includes robotic wood shaping, joint processing techniques, and auxiliary construction processes. In the case of mortise and tenon joint processing, the proposed method minimizes tool usage and achieves theprecise handling of various joint types, thereby reducing the time and labor associated with frequent tool changes. This approach simplifies the overall complexity of the traditional processing system, providing valuable insights for practical application and research within the construction sector.

In short, this study proposes an effective automated processing strategy and develops corresponding program modules and technical methods. The results provide new ideas and methods for the inheritance and development of traditional woodworking techniques in modern architecture and offer valuable references for the applications of robotic technology in the architectural field.

2. Methodology

The approach to digital woodworking based on the meta-model and coding system is illustrated in Figure 3. The steps for the automatic modeling method of the Building Information Model, grounded in meta-modeling and construction logic, are shown below:

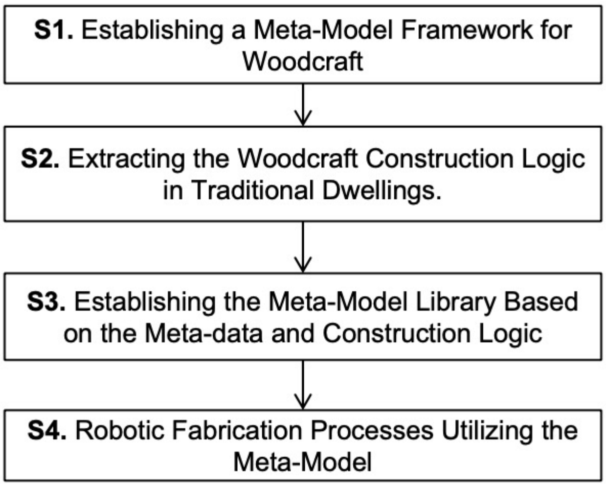


Figure 3. Digital construction process of woodcraft based on the meta-model.

1. Establishing the Meta-Model Framework. The initial step involves creating a meta-model framework for traditional timber buildings. This framework encompasses four aspects: meta-objects, meta-attributes, meta-relations, and meta-methods.
2. Extracting Woodcraft Construction Logic (Figure 4). The construction logic of woodcraft, including process classification, joinery relationships, and process sequences, is extracted and analyzed.

3. Building the Meta-Model Library. A meta-model library is created through the following steps:
    (a) Identifying the meta-objects and meta-attributes of traditional woodcraft and collecting the data;
    (b) Constructing a topological framework for all processes within the construction system according to the woodcraft construction logic;
    (c) Using modeling software tools to establish the meta-model based on the metadata and the topological framework.
4. Implementing Automatic Digital Construction. Combining the meta-model with digital construction tools, an automated digital construction model for woodcraft is created.

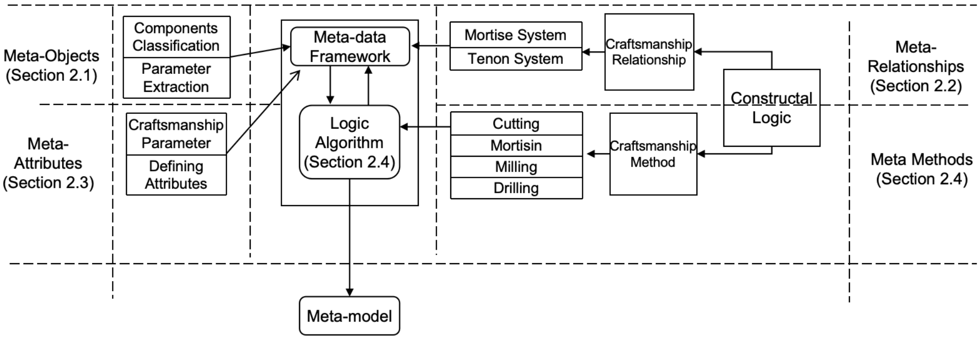


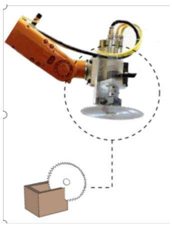
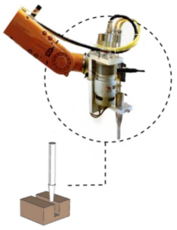
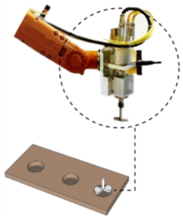
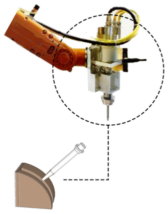
Figure 4. The proposed meta-model framework.

This method enables the rapid construction of highly complete and accurate digital construction information models for woodcraft, recording construction techniques with adjustable precision. As shown in Figure 4, the content related to meta-objects and meta-attributes pertains to conventional architectural elements. Meta-objects represent various woodcraft construction components, while meta-attributes denote information properties. Meta-relations and meta-methods are based on woodworking logic, with meta-relations encompassing joinery relationships and meta-methods representing digital construction methods for different craft types. Therefore, establishing a meta-model for woodcraft requires not only determining meta-objects and meta-attributes but also extracting the digital construction logic of woodcraft (Step 2). By integrating these logical elements, comprehensive digital modeling and automated construction of woodcraft can be achieved.

2.1. *Meta-Objects: Types of Craftsmanship*

The wooden structures of Bai dwellings feature a variety of connections, each with distinct characteristics based on their function and structure. To address the complexity of traditional timber joinery, a range of tools is employed to create mortise and tenon assemblies. The primary tools include saws, chisels, and planes. Traditionally, carpenters begin with saws to cut the wood, then use chisels for detailed work, especially in areas difficult to cut with a saw. Core craftsmanship includes lumber processing techniques, piercing and carving techniques, and planar woodworking techniques. To emulate the craftsmanship involved in mortise and tenon assembly, this study developed four robotic tools: a circular saw, a square chisel, an oscillating chisel, and a milling cutter, corresponding to robotic processes for cutting, mortising, drilling, and milling, respectively. By manually interchanging these tools, effective component processing is achieved, thereby enhancing and refining the technical system of robotic woodcraft construction. Table 1 illustrates the tools used for different types of craftsmanship.

Table 1. Table of craftsmanship techniques and tools.

Type of Craftsmanship	Traditional Tools for Specific Craftsmanship	Robotic Arms for Specific Craftsmanship
dfcxz Techniques (Surface Cutting)		
Piercing and Carving Techniques (Line Cutting)		 
Planar Woodworking Techniques (Point Cutting)		

(1) Lumber Processing—Surface Cutting

The lumber processing technique primarily involves cutting raw logs into the required billets. Axes and saws are indispensable tools in traditional practices. The axe is mainly used for chopping, splitting, shaping, and striking, while the saw is used for cutting, crosscutting, and tenon making. In modern woodworking, axes have gradually been replaced by various power saws, such as electric saws, chainsaws, and jigsaws.

This process corresponds to the circular saw tool in this study. As the first step in robotic craftsmanship, it involves the overall cutting of tenon-mortise components, primarily aimed at removing larger volumes of material.

(2) Piercing and Carving—Line Cutting

The piercing and carving technique involves fine processes such as joint adjustment and pattern carving. This mainly includes chiseling and drilling. Chisels are used to create mortise holes and slots and are typically used in conjunction with a hammer; drills are used for boring holes. With the mechanization and digitization of tools, traditional chiseling tools have been gradually replaced by electric drills, electric routers, and CNC milling machines.

This technique corresponds to the oscillating chisel and drilling tools in robotic craftsmanship. As the second step in the robotic process, it primarily includes chiseling and drilling operations, focusing on the processing of tenon-mortise openings and connection areas.

(3) Planar Woodworking—Point Cutting

The planar woodworking technique aims to achieve specific dimensions, shapes, and surface smoothness of wood to meet the requirements for width, thickness, and linear form of the workpiece. Traditional tools include the adze and plane, while modern machinery encompasses equipment such as jointers and thickness planers.

This process corresponds to the milling cutter tool in robotic craftsmanship. As the third step in the robotic process, it aims to achieve specific dimensions, shapes, and surface smoothness of the wood through planing, meeting the requirements for the width, thickness, and linear form of the workpiece. In decorative components, it is also used for intricate processes such as pattern-carving.

This systematic approach to robotic woodcraft integrates traditional woodworking techniques with modern robotic capabilities, offering a more efficient and precise method for creating complex wooden structures. The development of these specialized tools and processes represents a significant advancement in the field of architectural woodcraft, potentially revolutionizing the construction of wooden structures.

2.2. Meta-Relations: Topological Relationships between Tenon and Mortise

Mortise and tenon joints are fundamental connection methods in traditional Chinese woodworking. This joinery technique consists of two complementary parts: a protruding tenon and a recessed mortise. These joints have been widely used in ancient Chinese architecture, furniture, and other wooden structures in primary construction methods.

This study employs topological relationships in tenon and mortise joints to represent the meta-relation in the proposed meta-model.

From a meta-model perspective, we analyzed eight basic concave–convex connection topologies (numbered 1 to 8 in Figure 5). These topological relationships represent concrete implementations of the "cutting relationship" meta-concept, each embodying a specific cutting strategy. In the illustrations, red indicates the cutting module, while yellow represents the module being cut, visually demonstrating the characteristics of different cutting strategies.

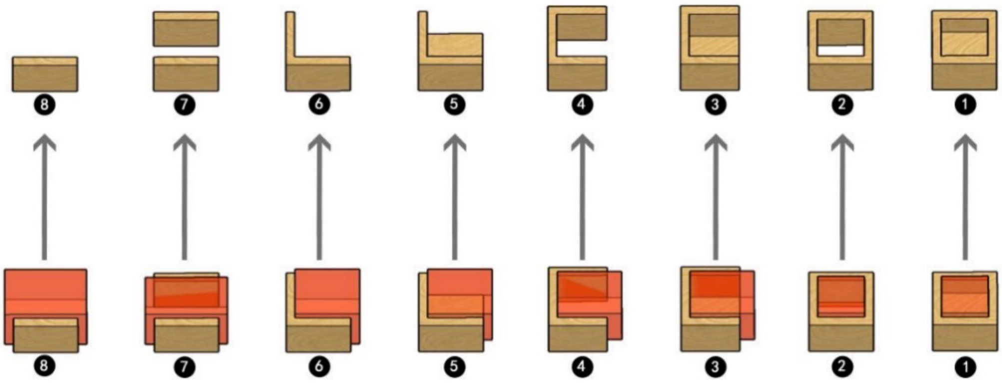


Figure 5. Illustration of cutting blocks and cut blocks.

We further categorized mortise and tenon connections into three basic types: nesting (Figure 6), protrusion (Figure 7), and intersection (Figure 8). The evolution process of these types, including steps, basic blocks, and final forms, reveals a core concept of the meta-model: diverse complex joint structures can be generated by combining basic cutting operations.

To implement this meta-relationship through robotic arms, we need to translate abstract cutting relationships into precise robotic movements and develop algorithms that interpret topological relationships to generate corresponding tool paths. This approach requires creating a system that can dynamically adjust cutting parameters based on specific mortise and tenon types, integrating sensors and feedback mechanisms to ensure accuracy in replicating complex traditional joint geometries. By defining mortise and tenon joints as the meta-relationship, we bridge ancient craftsmanship and modern robotic manufacturing, enabling the precise and efficient reproduction of these complex joints while maintaining their traditional integrity and function.

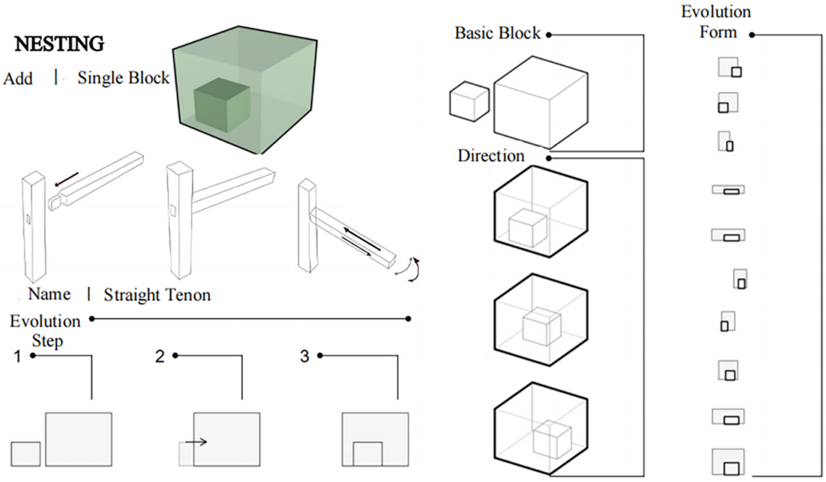


Figure 6. Mortise and tenon joint types: nested.

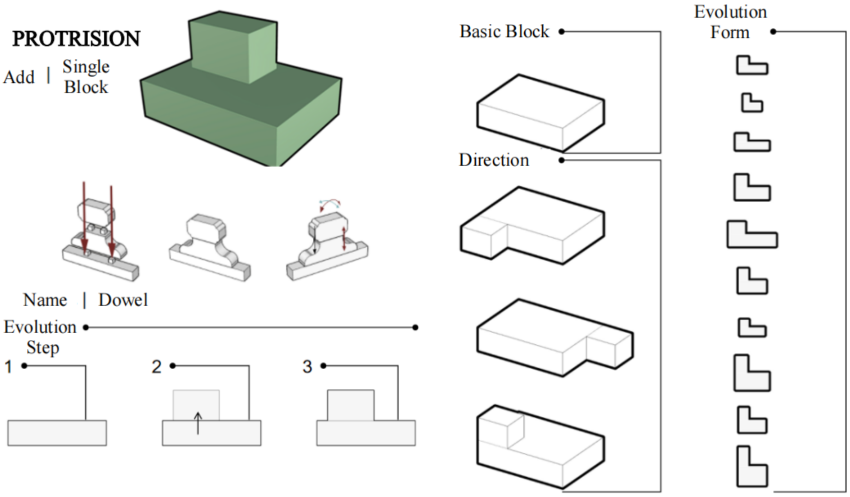


Figure 7. Mortise and tenon joint types: protruding.

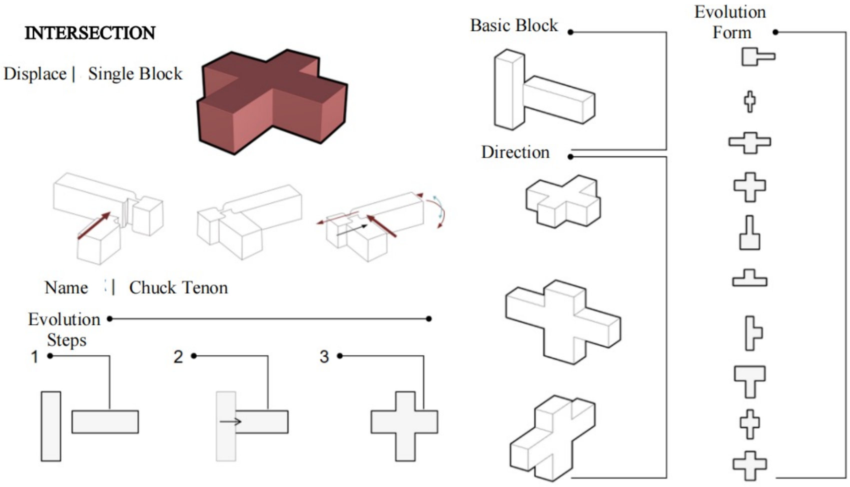


Figure 8. Mortise and tenon joint types: intersecting.

2.3. Meta-Attributes: Attributes of Tenon-Mortise Craft

A meta-attribute in a meta-model is a characteristic or property that describes attributes of the model elements themselves. Meta-attributes provide information about how the model is structured and how its elements should be interpreted or used.

In the context of tenon–mortise craftsmanship, meta-attributes could describe various aspects of the craft's knowledge representation, techniques, and principles, such as processing techniques, tool requirements, process planning, and precision control. In Dali Bai's traditional wooden architecture, joint connections vary based on function and structure, placing the tenon-mortise relationship at the core of advanced woodcraft. This complementary interaction defines the meta-relations in higher woodcraft. Various tenon-mortise components are manufactured using different tools and techniques.

In this study, we define robotic craftsmanship meta-attributes as cutting attributes. From a practical operation and robotic manufacturing standpoint, defining robotic craftsmanship meta-attributes as cutting attributes provides a clear, practical framework, particularly suited for designing and optimizing robotic manufacturing processes. The strength of this approach lies in its directness and operability, making the transition from concept to implementation more straightforward.

Robotic cutting can be classified into three primary topological types: surface cutting, line cutting, and point cutting (Figure 9). Each type can be further refined into multiple process levels based on the number of cutting surfaces and their relative positions. Different process levels correspond to various robotic end effectors and processing techniques.

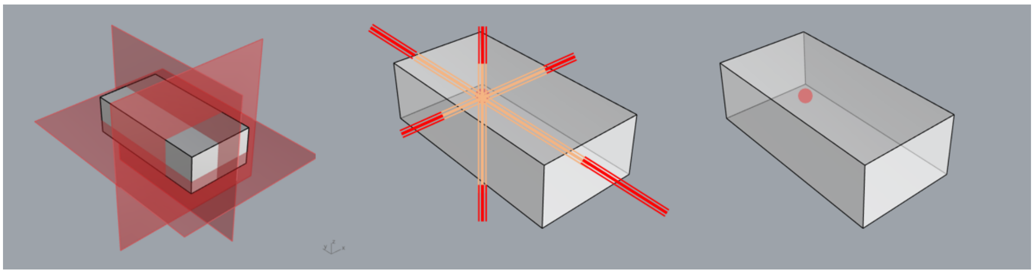


Figure 9. Illustrative examples of surface, line, and point cutting.

(1) Surface Cutting

Surface cutting refers to a cutting method where the cutting plane is located on the surface or within the workpiece (Figure 10). It is suitable for simple processing edges where the cutting line jumps at corners or edges. This cutting process can be executed using a circular saw or a vibrating chisel.

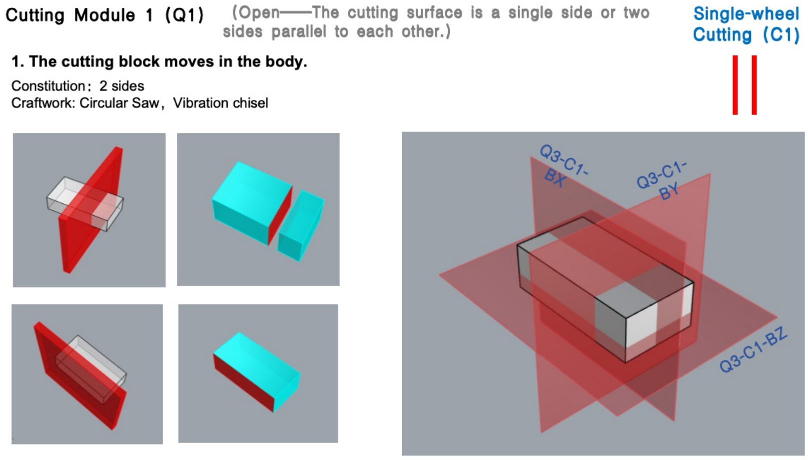


Figure 10. Surface cutting.

(2) Line Cutting

Line cutting refers to a cutting method performed along the edges of the workpiece and can also be divided into three levels: line cutting on the edge (Figure 11), line cutting on the surface (Figure 12), and line cutting in the interior (Figure 13).

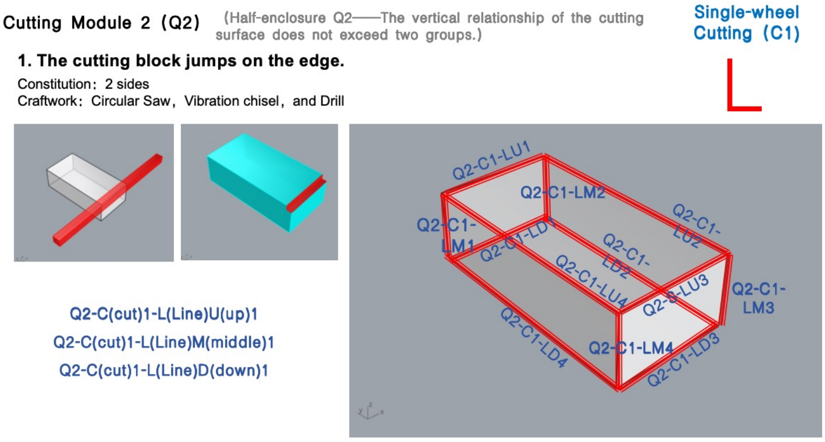


Figure 11. Line cutting: on the edge.

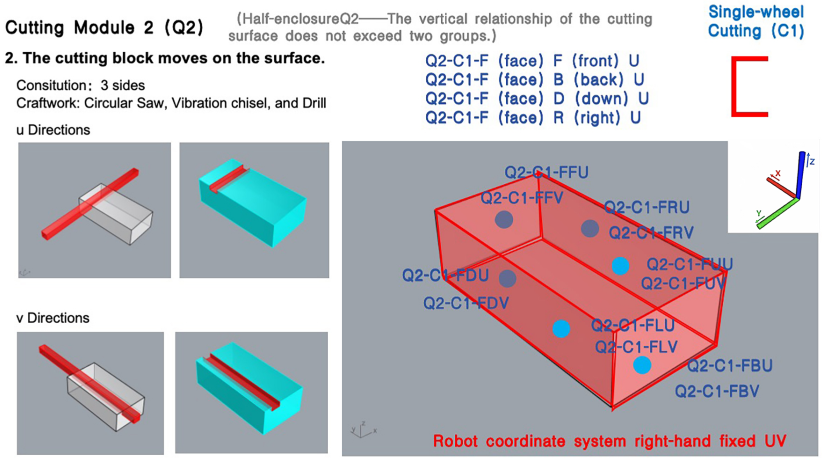


Figure 12. Line cutting: on the surface.

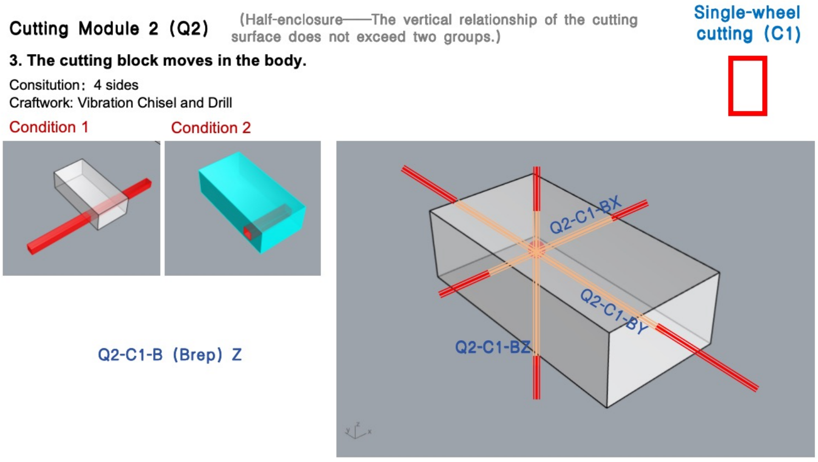
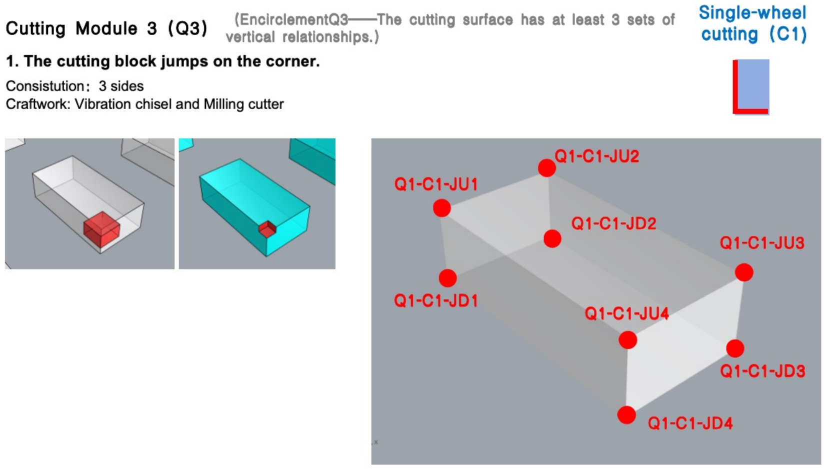


Figure 13. Line cutting: in the body.

(3) Point Cutting

Point cutting refers to localized cutting performed at the corners of the workpiece and has three cutting types as shown in Figures 14–16.



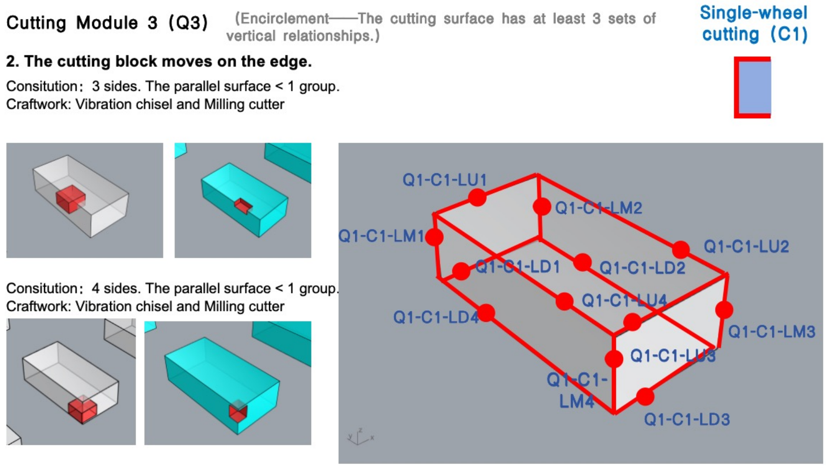
Cutting Module 3（Q3） （EncirclementQ3——The cutting surface has at least 3 sets of vertical relationships.）

Single-wheel cutting（C1）

1. The cutting block jumps on the corner.

Consistution：3 sides
Craftwork: Vibration chisel and Milling cutter

Figure 14. Point cutting: on the corner.



Cutting Module 3（Q3） （Encirclement——The cutting surface has at least 3 sets of vertical relationships.）

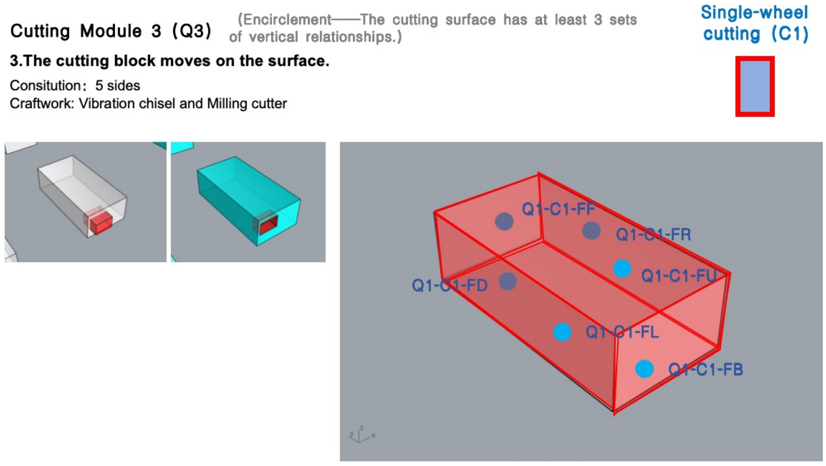
Single-wheel cutting（C1）

2. The cutting block moves on the edge.

Consitution：3 sides. The parallel surface < 1 group.
Craftwork: Vibration chisel and Milling cutter

Consitution：4 sides. The parallel surface < 1 group.
Craftwork: Vibration chisel and Milling cutter

Figure 15. Point cutting: on the edge.



Cutting Module 3（Q3） （Encirclement——The cutting surface has at least 3 sets of vertical relationships.）

Single-wheel cutting（C1）

3.The cutting block moves on the surface.

Consitution：5 sides
Craftwork: Vibration chisel and Milling cutter

Figure 16. Point cutting: on the surface.

2.4. Meta-Method and Logic Algorithm

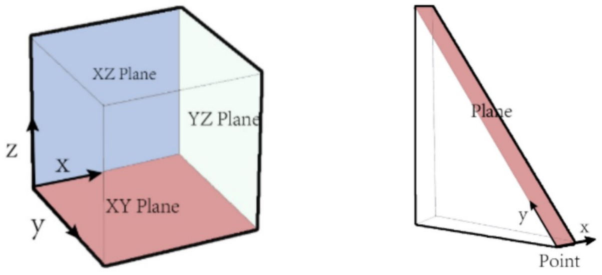
In the meta-model, meta-methods and logic algorithms play crucial roles. Meta-methods define high-level strategies and steps for problem-solving, providing a general methodological framework for specific domains. Logic algorithms, on the other hand, are the concrete computational processes that implement these methods and are responsible for processing data, executing operations, and deriving results. The two complement each other, jointly forming the core operational mechanism of the meta-model.

In this study, we describe the traditional mortise and tenon craftsmanship of Bai ethnic wooden structures through a meta-model and apply it to guide robotic arms in creating various types of mortise and tenon joints. The meta-methods of traditional woodworking primarily include four aspects: cutting, mortising, milling, and drilling. When applied to robotic arm operations, these meta-methods are transformed into the following parametric designs: circular saw cutting path parametric design, square chisel mortising path design, milling path design, and drilling path design (Section 2.4.1). To achieve efficient robotic arm operation, we employ a logic algorithm that optimizes the selection of processing techniques by rounds as introduced in Section 2.4.2.

2.4.1. Meta-Methods

(1) Circular Saw Cutting Path Design

The circular saw cutting path design primarily employs parameterized Boolean operations. First, the required subtraction model is calculated and extracted based on the 3D model of the component. Then, the subtraction model is parameterized and decomposed, extracting key cutting surfaces, boundary lines, and reference points. Based on the circular saw radius, the starting and ending reference points are offset to ensure cutting accuracy. Next, the reference points are arranged and combined according to the construction sequence, and each reference point is assigned an appropriate working plane based on the cutting surface location and direction (Figure 17). By adjusting parameters such as the cutting surface, circular saw radius, etc., the optimal cutting path scheme can be achieved.



(**a**) (**b**)

Figure 17. Diagram of working planes. (**a**) Flat-cutting work plane, (**b**) inclined cutting work plane.

Moreover, based on the angle relationship between the cutting surface and the base surface of the workpiece, the circular saw's cutting process can be divided into two scenarios: planar cutting and inclined cutting. For planar cutting, the basic working plane is directly assigned (Figure 18); for inclined cutting, the cutting line vector and its normal vector are calculated, and the inclined working plane is constructed by a vector combination (Figure 19).

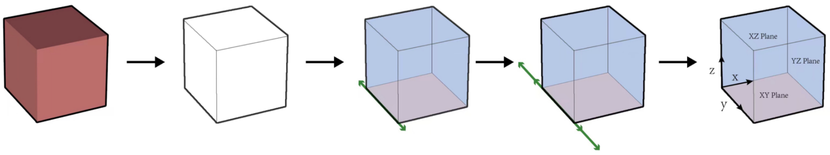


Figure 18. Planar cutting path design methodology.

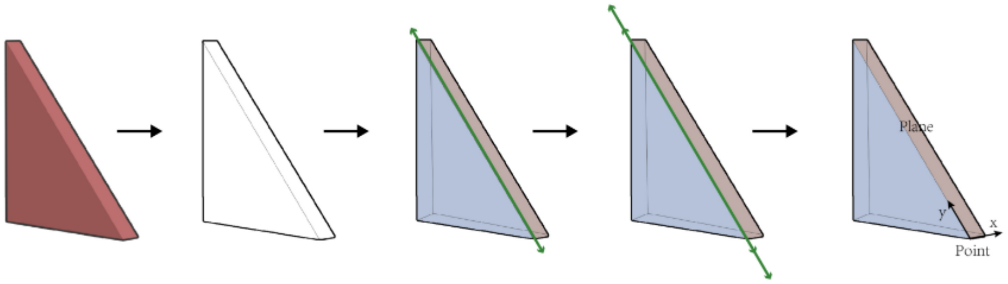


Figure 19. Inclined cutting path design methodology.

(2) Square Chisel Mortising Path Design

The design of the square chisel mortising path is based on the parameterized treatment of the subtraction model. This process begins with calculating and extracting a rectangular subtraction model, followed by isolating its top surface. The top surface is then segmented and meshed according to the chisel tool's end dimension and surface length, yielding midpoints that serve as path reference points. To accommodate the robotic arm's tool coordinate system, which is centered on the chisel tool, these midpoints are shifted to the bottom surface. A data weaving algorithm subsequently arranges these adjusted points in a zigzag pattern, forming the processing path. Given the regular rectangular shape of the subtraction model, the basic working plane can be directly assigned to complete the path design. Figure 20 presents the process of square chisel mortising.

The processing path can be rapidly optimized and output by adjusting parameters such as chisel tool size and mesh density. This approach allows for efficient and precise mortising operations in robotic woodworking applications.

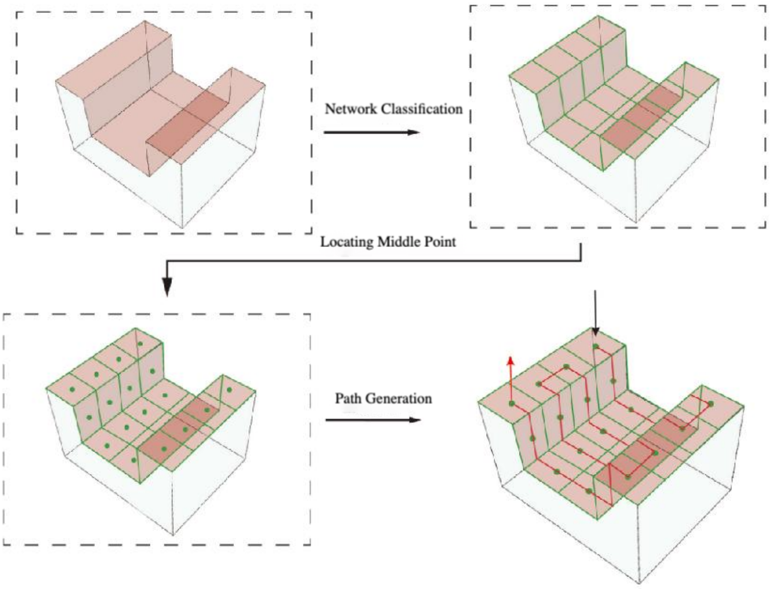


Figure 20. Square chisel mortising process.

(3) Milling Path Design

The milling path design method primarily comprises two approaches: row cutting and contour cutting. Row cutting is suitable for complex surfaces with large curvatures, such as spherical surfaces and variable cross-sections, while contour cutting is primarily used for machining components with irregular cross-sectional surfaces.

In row cutting, key curved surface parameters like arc origin and edge length are first extracted from the subtraction model. Reference lines are then arrayed and offset along the arc edge's tangent direction, with intervals equal to the milling cutter's layer feed rate. These reference lines are divided and combined to obtain initial path points. As the working plane changes with the cutting position, yjr tangent and normal vectors are extracted for each path point, and the corresponding working plane is constructed through vector combination.

Contour cutting begins by layering the subtraction model into contours, each corresponding to a milling-layer feed depth. These contours are offset inward by the milling cutter radius to form the outermost processing path, then offset equidistantly inward to obtain complete path lines. The divided points on these path lines serve as path control points, with the working plane determined directly by the layer-cutting direction vector. These methods enable precise and efficient milling operations for various surface types in robotic woodworking applications. The milling path design is illustrated in Figure 21.

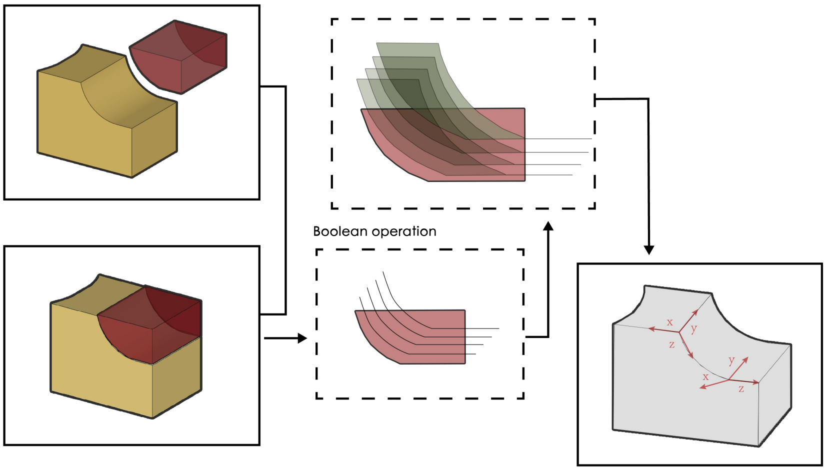


Figure 21. Milling cutter process.

(4) Drilling Path Design

The drilling path design is illustrated in Figure 22. Drilling processes primarily focus on machining round holes, such as mortises. The process begins with the batch selection of round hole subtraction models, followed by tree data processing to obtain geometric information including the surface parameters, central axis, and cylinder height for each hole. The algorithm extracts the starting and ending points on the axis and assigns an appropriate working plane based on the hole direction. To prevent interference between the robotic arm and the component during operation, the starting point is typically offset slightly along the axis.

The final step involves matching the arranged and combined path control points with their corresponding working planes, thus completing the drilling path design. This algorithm's flexibility allows for adaptation to various drilling requirements by adjusting parameters such as hole depth and inter-hole distance. This streamlined approach ensures efficient and precise drilling operations in robotic woodworking applications while maintaining adaptability to diverse project needs.

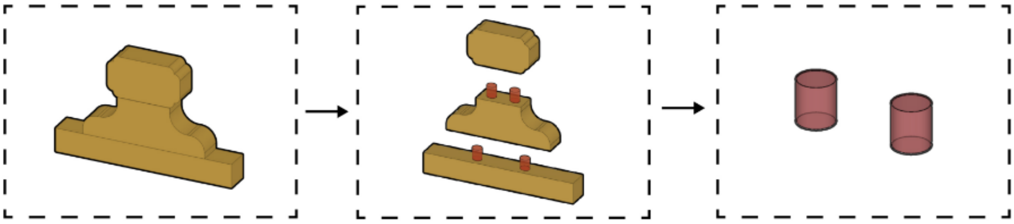


Figure 22. Silver ingot tenon hole-making process.

2.4.2. Logic Algorithm: Optimization of Processing Techniques Based on a Genetic Algorithm

The implementation process of the logic algorithm is shown as follows (Figure 23):

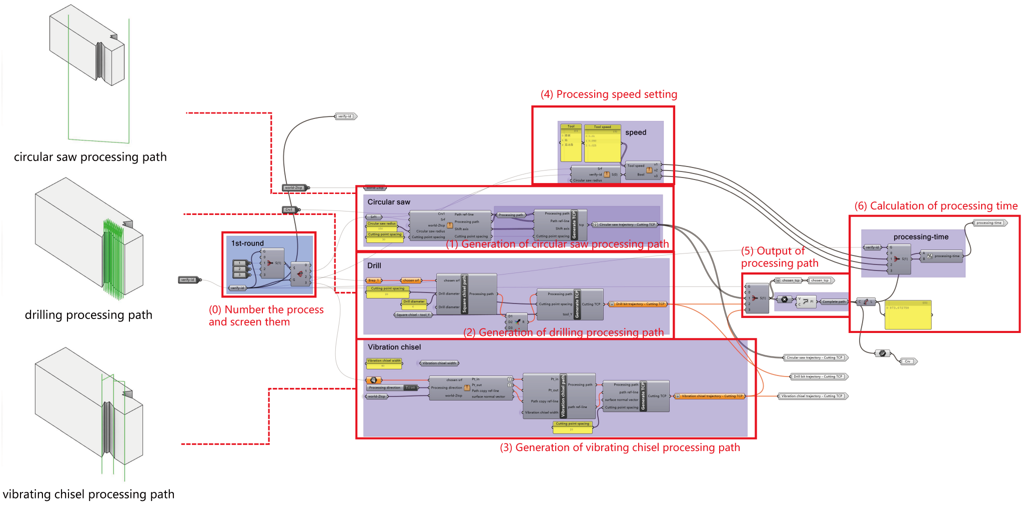


Figure 23. Overall flowchart.

The logic algorithm provides a systematic approach to transforming complex traditional woodworking techniques into optimized, executable instructions for the robotic fabrication of mortise and tenon joints. This method not only preserves the essence of traditional craftsmanship but also improves production efficiency and precision, providing new technical support for the protection and inheritance of traditional wooden residential structures.

2.4.3. Specific Implementation Process and Code

1. Geometric Decomposition. The algorithm begins by breaking down complex mortise and tenon joints into simple geometric shapes. This step involves extracting machining surface elements from these shapes, which serve as geometric references for subsequent processing stages. The process is illustrated in Figure 24.

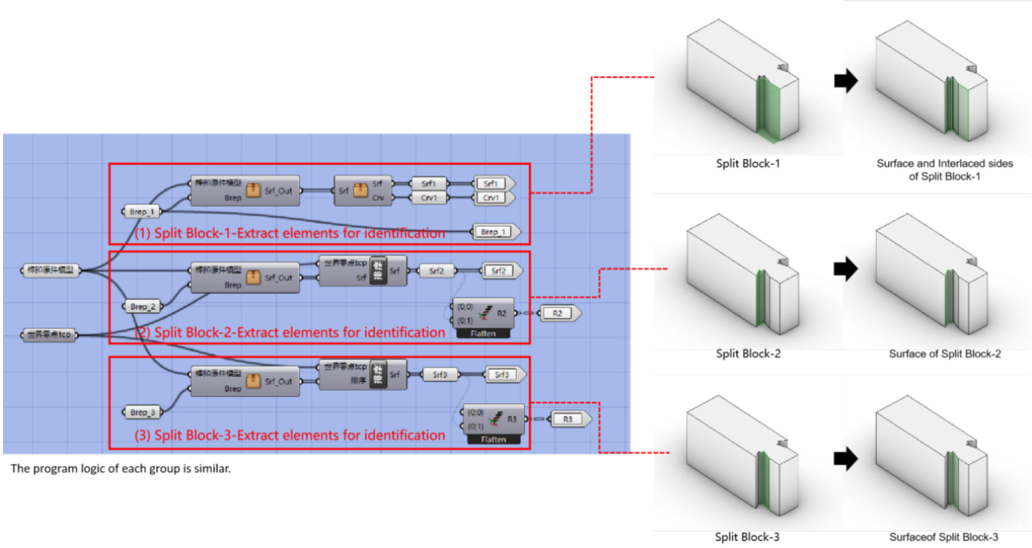


Figure 24. Workpiece splitting diagram.

2. Sequential Program Generation. Based on the sequence of decomposed geometric shapes, the algorithm creates a series of staged processing programs. Each stage follows

a consistent logic: (a) assigning unique identifiers to different processing techniques, (b) analyzing the machining surface elements specific to that stage, and (c) generating potential machining paths and estimating processing times for various techniques. The process is illustrated in Figure 25.

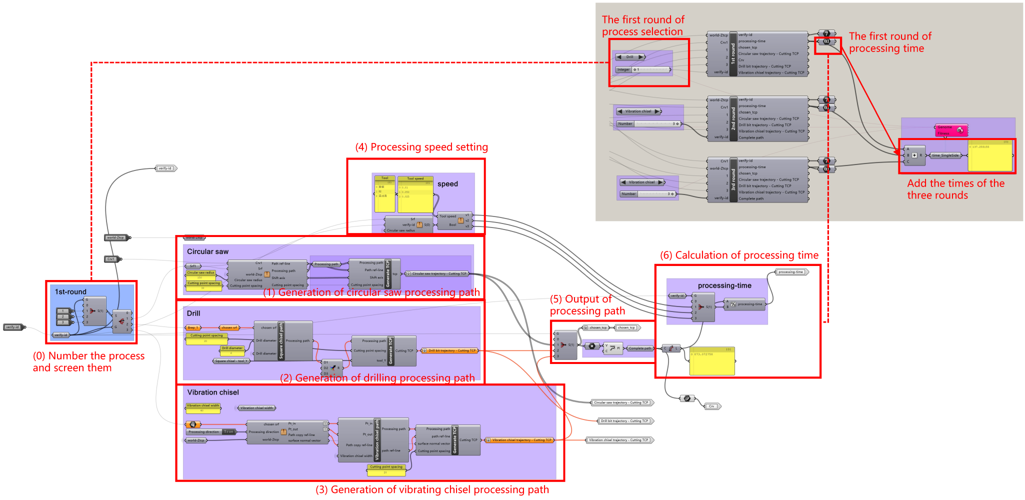
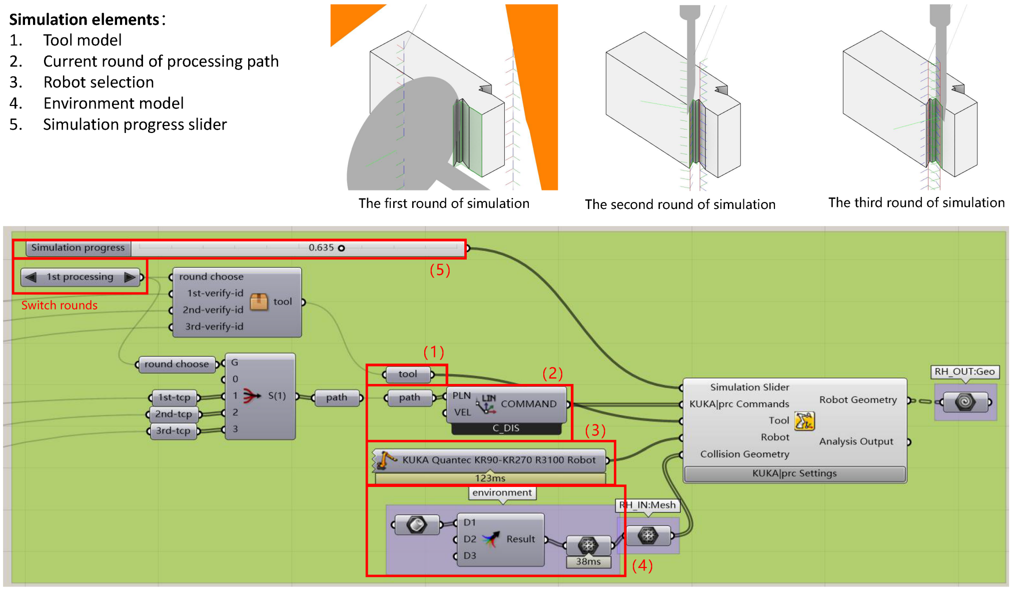


Figure 25. Iteration process flowchart.

3. Optimization through a Genetic Algorithm. The algorithm employs a genetic algorithm to evaluate and select the optimal process number for each stage. This optimization considers predefined conditions and constraints, aiming to determine the most efficient overall machining path. The process is illustrated in Figure 26.


Simulation elements:

1. Tool model
2. Current round of processing path
3. Robot selection
4. Environment model
5. Simulation progress slider

Figure 26. Genetic algorithm optimization flowchart.

4. Path Integration and Code Generation. The final step involves integrating the optimized machining paths with tool models and other relevant parameters. This integrated data are then processed to generate (a) a comprehensive machining strategy, and (b) detailed instructions for robotic arm operations. The process is illustrated in Figure 27.

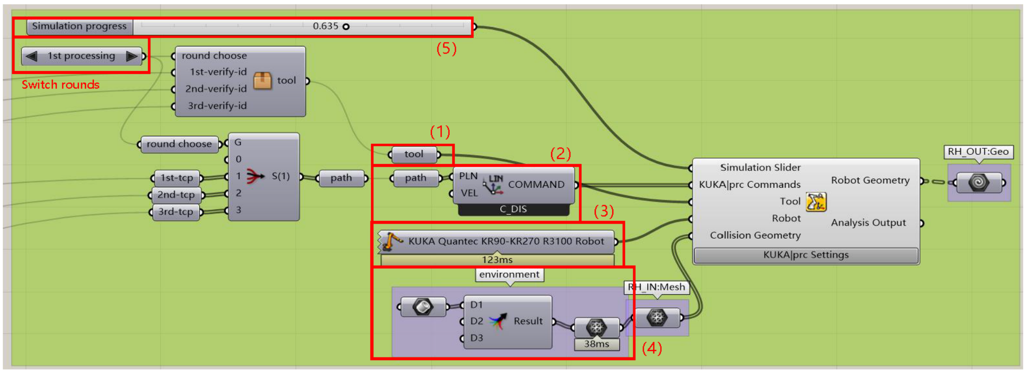


Figure 27. Process simulation diagram.

3. Experiments

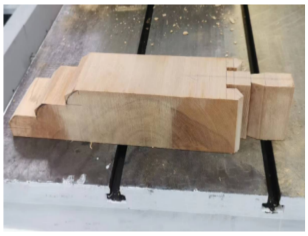
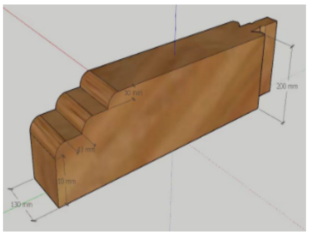
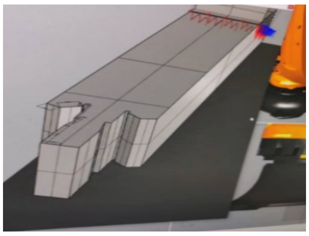
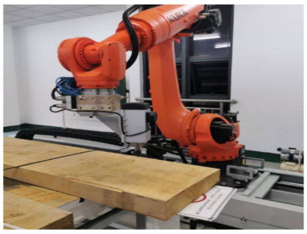
To evaluate the practicality of the proposed methodology for construction projects, this study conducted a set of empirical performance assessments. It compared the fabrication of seven typical mortise and tenon joints common in traditional Chinese wooden architecture, using both conventional CNC machinery and an advanced robotic arm approach. The joints include dovetail tenon with sleeves and half shoulders (“二肩蹬榫”), straight tenon (“直榫”), dovetail (“燕尾榫”), chuck tenon (“夹头榫”), through tenon (“穿榫”), purlin (“檩条”), and column head (“柱头”). The study focuses on key performance metrics: assembly planning functionality, task completion time, cutting precision, and material waste.

The robotic arm experiments followed a systematic procedure. First, a wooden board closely matching the sample tenon’s dimensions was selected. After confirming the programming and simulation conditions, the board’s dimensions were measured, and it was securely fixed to the workbench. The milling process, controlled by trajectory input information from KUKA | PRC software (Version KUKAprcGH), executed the material reduction. The G-code generated by KUKA | PRC© was then imported into the robot’s control system to manufacture the wooden prototype. Table 2 shows selected images of experimental results, three-dimensional simulations, and the experimental process for the dovetail tenon, one of the seven research objects.

To illustrate the experimental procedures, we use a dovetail tenon as an example (Figure 28). This joint is known for its unique and intricate geometry in traditional Bai ethnic group wooden structures. The process begins by defining two primary components in the meta-model: red and yellow rectangles, representing raw materials. These basic shapes are then transformed into complementary mortise and tenon structures through a series of sophisticated machining operations. The key stages of the cutting process are shown below.

1. Incline Cutting: creating an inclined plane at one end of the yellow component, essential for subsequent precision machining.
2. Contour Cutting: forming a complex polygonal cross-section on the inclined plane, enhancing joint intricacy and stability.
3. Difference Operation: subtracting the yellow component’s contour from the red component to create a matching grooved structure.
4. Union Operation: combining the modified red component with the yellow component to form a precise mortise and tenon connection.

Table 2. Illustrative example of the experimental result, stimulation, and experimental process.

Dovetail Tenon Experimental Results		
Dovetail Tenon 3D Simulation		
Dovetail Tenon Experimental Process		

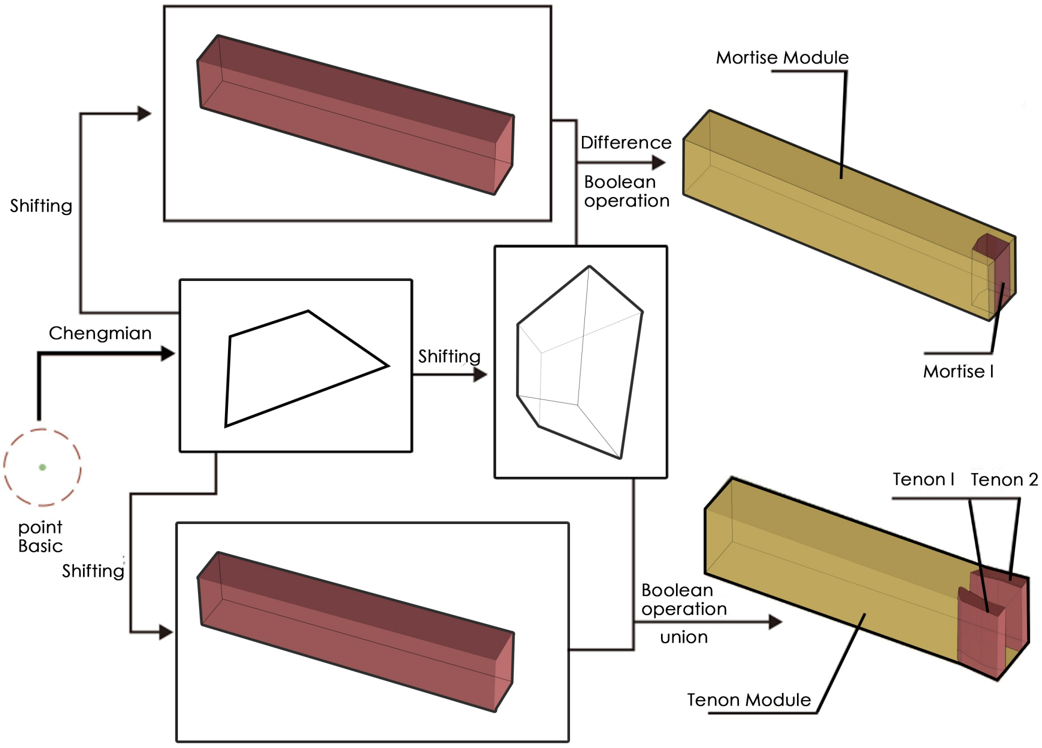


Figure 28. Generation of the module for the dovetail tenon element model topology.

4. Experimental Results and Discussion

To intuitively reflect the effects of the proposed robotic arm approach, this study compares it with commonly used traditional CNC machines. The evaluation of the experimental results primarily includes the analysis of automatic assembly planning functions, task response times, and the analysis of cutting precision and material waste to evaluate the efficiency of timber usage.

4.1. Path Optimization Comparison

This study evaluated the feasibility of two systems under different slicing-path-planning strategies, using a mortise and tenon joint as an example. The assessment was based on the five key performance indicators shown in Table 3, which presents the assembly information and system planning feasibility probabilities. Figure 29 displays the results in the system which is summarized in Table 3.

Table 3. Comparison of the assembly planning function test results.

Assembly Planning Test	Proposed Method	Traditional CNC Machining
1. Running Distance	4243.54 mm	11,993.79 mm
2. Robot Arm Lifting Times	5 times	11 times
3. Wood Consumption	17%	100%
4. Overlapping Layers	6 layers	22 layers
5. Running Time	275 s (35 s/layer)	2399 s (62 s/layer)

The results indicate a significant performance difference between the proposed method and traditional CNC machine tools (Figure 29). Our genetic algorithm-based cutting path planning outperforms the digital machine tool in all measured metrics. Specifically, our method reduces running distance by 64.62% (4243.54 mm vs. 11,993.79 mm), decreases robot arm lifting frequency by 55% (5 vs. 11), improves wood utilization by 83% (17% consumption vs. 100%), reduces overlapping layers by 73% (6 vs. 22), and shortens running time by 88.54% (275 s vs. 2399 s). Therefore, the proposed cutting path optimization strategy significantly enhances wood-cutting efficiency, whereas traditional CNC machine tools are less effective in material usage, operating distance, and layer reduction.

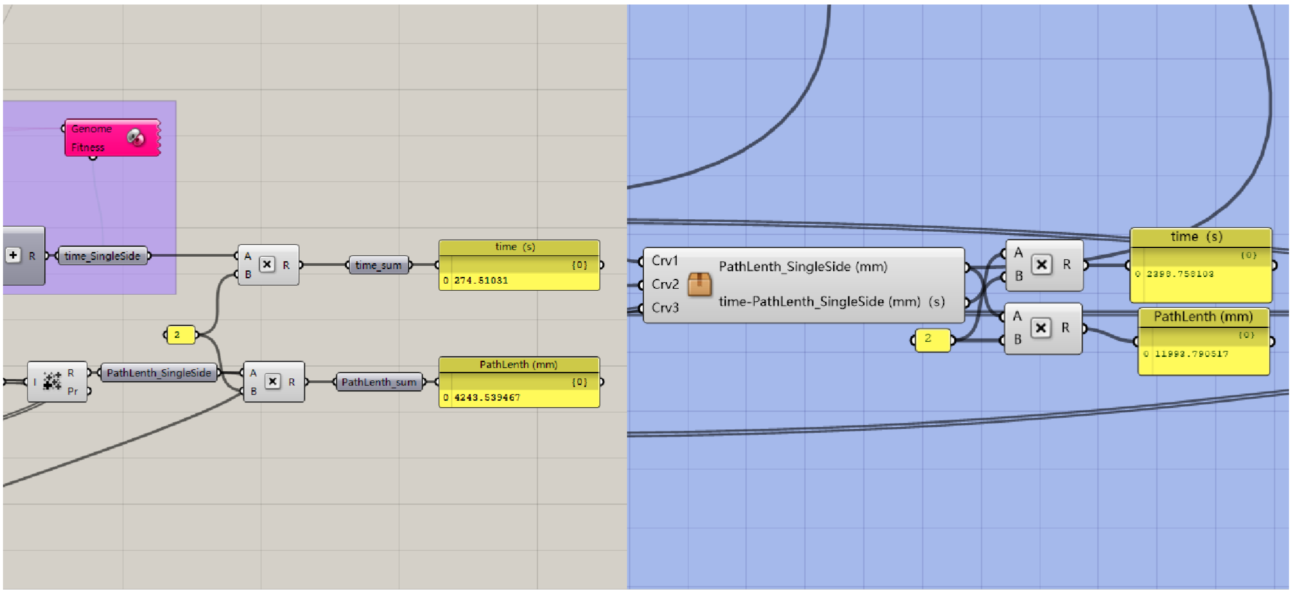


Figure 29. Results of path length and processing times in the stimulation.

The most notable improvement is in the reduction in wood consumption. Traditional CNC machines typically leave only low-value sawdust after cutting, resulting in substantial material waste. In contrast, our method significantly enhances wood utilization, minimizing waste and lowering production costs.

These findings clearly demonstrate that the genetic-algorithm-based cutting path optimization markedly improves wood-cutting efficiency. The traditional digital machine tool, constrained by its existing path, exhibits inferior performance in material utilization, running distance, layer reduction, and overall processing time. This comparison underscores the proposed method's significant advantages in wood processing efficiency and resource utilization, offering a more economical and environmentally friendly solution for the woodworking industry.

4.2. Task Response Time Comparison

Besides path optimization, the system's response speed to various tasks largely determines the effectiveness of the proposed system. Therefore, this study examines the response time of the two systems when handling the same tasks.

The experimental results show that the average response time of the proposed system is 37,067 s, while the CNC machine's average response time is about 61,645 s. These data indicate a clear advantage for the wood component's cutting path optimization system based on the genetic algorithm. Supported by this algorithm, the system reduces the time and spatial overhead during operation to a certain extent, increasing its response speed to various tasks. It maintains high efficiency even as task volumes surge in the later stages of the project, accelerating the processing progress of wooden prefabricated components.

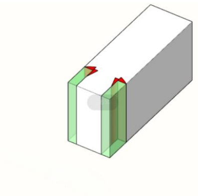
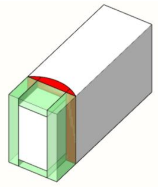
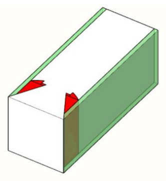
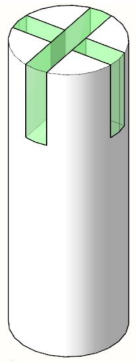
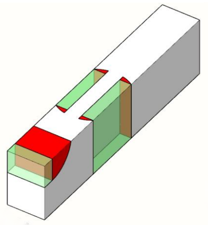
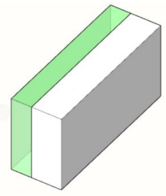
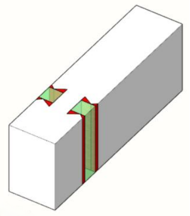
4.3. Analysis of Cutting Precision and Material Waste

Table 4 presents a comparative analysis of the seven selected types of tenon and mortise assembly employing CNC machining versus our proposed methodology. Red areas indicate overlapping regions processed by both systems, while green sections represent additional components exclusively fabricated by our robotic-arm-based approach. It is important to note that in the CNC manufacturing process, the green areas would typically be milled into virtually valueless sawdust by the machine. However, with our method, these green areas remain as solid wood blocks that can be repurposed for other uses. Therefore, the green transparent sections can be viewed as material saved through the implementation of our approach, highlighting the improved material efficiency of our method compared to traditional CNC machining.

The study reveals significant improvements in material conservation across different mortise and tenon structures using our proposed methodology compared to traditional CNC machining. Chuck tenon and column head configurations exhibited the highest material utilization, conserving 4.37 and 4.23 m^3, respectively. Even structures with lower absolute savings, such as the dovetail tenon with sleeves and half shoulders and straight tenon designs (0.131 and 0.139 m^3, respectively), showed marked improvement over conventional methods. Intermediate savings were observed for through tenon (0.54 m^3), dovetail (0.22 m^3), and purlin (0.96 m^3) structures. Crucially, across all types of joints examined, our approach consistently outperformed traditional techniques, demonstrating its superior efficiency in material conservation.

These findings highlight the fact that precise parametric cutting techniques enable material waste minimization without compromising structural integrity. Notably, while CNC machining produces only low-value sawdust as waste, our robotic-arm-based approach leaves behind wood blocks that can be reused or recycled, further enhancing sustainability. This method not only reduces construction costs but also significantly diminishes the environmental impact.

Table 4. Tenon and mortise comparison

Selected Tenon and Mortise	**Dovetail Tenon with Sleeves and Half Shoulders (“二肩蹬榫”)**	**Straight Tenon (“直榫”)**	**Dovetail (“燕尾榫”)**	**Column Head (“柱头”)**
Material Saved (Green Areas)	0.131 m^3	0.139 m^3	0.22 m^3	4.37 m^3
Cutting Module	Q1 + Q2	Q1 + Q2 + Q3	Q2 + Q3	Q1 + Q2
Image				
Selected Tenon and Mortise	Chuck tenon (“夹头榫”)	Through tenon (“穿榫”)	Purlin (“檩条”)	
Material Saved (Green Areas)	4.23 m^3	0.54 m^3	0.96 m^3	
Cutting Module	Q1 + Q3	Q1 + Q2	Q1 + Q2	
Image				

Note: Q1, Q2, and Q3 refer to the cutting modules introduced in Section 2.3. Q1 represents surface cutting using circular saws; Q2 represents line cutting using vibration and piercing chisels; and Q3 represents point cutting using milling cutters.

4.4. Discussion

This study introduces an innovative approach to sustainable timber construction by integrating traditional woodworking techniques with advanced robotic technology. At its core is a meta-model-based parametric design framework that optimizes robotic cutting processes. Experimental results demonstrate that this proposed method significantly enhances wood utilization efficiency compared to conventional CNC machining.

Parametric design, a methodology widely used in architecture, serves as the foundation for this approach. The application of these techniques to standardize traditional mortise and tenon joints enables the rapid generation of joint geometries, thereby facilitating detailed design and optimization processes. This standardized approach not only supports batch and industrial design and construction but also allows for customization as needed. Compared to batch model creation, standardization offers superior management of the complexities inherent in traditional wooden structures and their diverse components. While digital machining tools can quickly generate conventional elements such as dovetail tenons, more intricate surfaces, and specialized parts require advanced digital techniques. Consequently, our tools and path-planning programs demonstrate high practicality in addressing these complex requirements.

For instance, the mortise and tenon components in Jianchuan residential architecture exhibit significant variation, requiring diverse cutting models tailored to specific positions, with numerous nodes demanding production. This complexity surpasses the capabilities of traditional digital machining. However, through the standardized process developed in this study, wooden structures can be rapidly analyzed and their cutting models efficiently planned, resulting in substantial labor conservation. The process is streamlined to the extent that it merely requires the insertion of the cutting model to finalize the path design.

The alignment of wooden architecture with modern sustainability principles is noteworthy. As construction technology advances, the processing of wooden structures is transitioning from industrialized methods to digitalized ones. This shift has brought attention to construction robots, which offer enhanced environmental adaptability, efficient production modes, and high-quality outcomes. These advantages have attracted architects seeking to improve the efficiency of the construction life cycle. Currently, extensive research is being conducted into the application of robots in construction, with industrial robotic arms and their derivatives being the most prevalent. A prime example of robotic construction is the No. 2 Visitor Center of Nanjing Garden Expo Park in China, as illustrated in Figure 30. This building shows the potential of robotic systems in creating complex architectural structures.

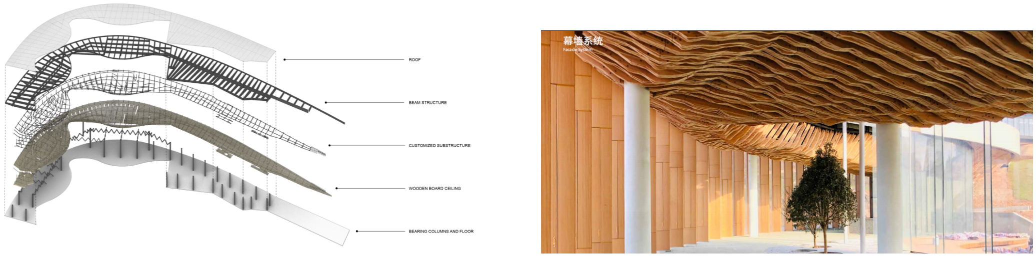


Figure 30. Robotic construction example: No. 2 Visitor Center of Nanjing Garden Expo Park.

While this study delves into wooden structure processing technologies, employing architectural robotics and parametric design to ensure seamless data connectivity from design to construction, several issues remain to be addressed.

Firstly, the standardized process outlined here sets the stage for future digital platform development. Future research could focus on creating such a platform, utilizing graphics technology to optimize path planning and streamlined steps for factory applications.

Secondly, the integrated design and construction proposal presented in this study has broad applicability. Specifically, this study addresses path planning for robotic arm processes. Future research could explore the principles of knowledge graphs to deduce positional relationships. This would enable digital monitoring, collaborative management, and digital twin production, ultimately achieving integrated and automated applications of artificial intelligence and robotics.

In short, this study demonstrates the potential of combining traditional woodworking techniques with modern technology to enhance sustainability and efficiency in construction. The proposed framework not only addresses current challenges but also paves the way for future advancements in the field.

5. Conclusions

This research presents innovative approaches for sustainable timber application in construction, focusing on three core objectives: craftsmanship inheritance, material conservation, and efficiency enhancement. Our findings yield the following conclusions.

Craftsmanship Inheritance. This study successfully integrates traditional mortise and tenon techniques with modern parametric design by developing a meta-model-based cutting relationship analysis system. This digital approach preserves traditional woodworking techniques while adapting them to contemporary construction needs. By identifying and optimizing six typical mortise and tenon structures, this study has paved new paths for the preservation and innovative application of traditional craftsmanship.

However, the integration of robotic technology with traditional woodworking methods faces two main challenges:

- *Measurement accuracy:* The current reliance on manual measurements introduces subjectivity and potential errors; integrating machine vision technology could improve precision and efficiency by scanning entire components and obtaining accurate coordinate parameters.
- *Balancing craftsmanship preservation with digitalization:* There is a need to develop advanced digital platforms that incorporate machine learning technologies to simulate traditional craftsmen's styles and techniques; this would optimize path planning and make the design process more human-centric and stylized, better adapting to factory construction environments while preserving traditional craftsmanship.

Material Conservation. Precise parametric cutting design significantly reduced material waste. Our methods resulted in a total material savings of 10.589 m^3 for the six mortise and tenon structures, lowering the waste rate to 6.5% compared to traditional CNC machining. These findings underscore the potential of optimized design in minimizing material waste, offering practical solutions for sustainable construction.

Efficiency Enhancement. The proposed parametric design framework substantially improved design and production efficiency. By simplifying complex structures into controllable parameters and cutting operations, rapid customization and optimization can be achieved. Compared to traditional CNC systems, improvements were noted in software path optimization (12%), nozzle lift frequency (45%), wood consumption (17%), overlap layer optimization (27%), and runtime (15%). These advancements accelerate the design process and lay the groundwork for large-scale prefabricated production.

This research provides novel perspectives on sustainable timber application in construction. By balancing traditional craftsmanship, modern technology, and environmental concerns, significant contributions are made to the industry's sustainable future. The approach combines the inheritance of craftsmanship with innovation, offering practical solutions through precise material utilization and efficiency improvement.

Future research should expand this framework to more complex timber structures and larger-scale projects, further promoting environmentally friendly and efficient practices in the construction industry. Additionally, addressing the challenges related to measurement accuracy and the balance between craftsmanship preservation and digitalization will be crucial for advancing the integration of robotic technology and traditional woodworking methods.

Author Contributions: Conceptualization, Z.L.; Methodology, Z.L.; Software, Y.X.; Validation, H.L.; Formal analysis, Y.X.; Investigation, Z.C.; Writing—original draft, L.H.; Writing—review & editing, Z.C.; Visualization, Z.C. and H.L.; Supervision, Z.L.; Project administration, Z.L. and L.H.; Funding acquisition, L.H. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by Guangxi First-class Discipline Statistics Construction Project Fund, as well as the Guangxi Young and Middle-aged Higher Education Faculty Research Capabilities Enhancement Project (Grant No. 2024KY0665).

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: Author Yingying Xiao was employed by the company Tongji Architectural Design (Group) Co. Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Wang, L.; Toppinen, A.; Juslin, H. Use of wood in green building: A study of expert perspectives from the UK. *J. Clean. Prod.* **2014**, *65*, 350–361. [CrossRef]
2. Hildebrandt, J.; Hagemann, N.; Thrän, D. The contribution of wood-based construction materials for leveraging a low carbon building sector in Europe. *Sustain. Cities Soc.* **2017**, *34*, 405–418. [CrossRef]
3. Moore, J.; Cown, D. Processing of wood for wood composites. In *Wood Composites*; Elsevier: Amsterdam, The Netherlands, 2015; pp. 27–45.

4. Menges, A.; Schwinn, T.; Krieg, O.D. *Advancing Wood Architecture*; Taylor & Francis: Abingdon, UK, 2016.
5. Petersen, K.H.; Napp, N.; Stuart-Smith, R.; Rus, D.; Kovac, M. A review of collective robotic construction. *Sci. Robot.* **2019**, *4*, eaau8479. [CrossRef] [PubMed]
6. Gharbia, M.; Chang-Richards, A.; Lu, Y.; Zhong, R.Y.; Li, H. Robotic technologies for on-site building construction: A systematic review. *J. Build. Eng.* **2020**, *32*, 101584. [CrossRef]
7. Chang, S.; Siu, M.F.F.; Li, H.; Luo, X. Evolution pathways of robotic technologies and applications in construction. *Adv. Eng. Inform.* **2022**, *51*, 101529. [CrossRef]
8. Saidi, K.S.; Bock, T.; Georgoulas, C. Robotics in construction. In *Springer Handbook of Robotics*; Siciliano, B., Khatib, O., Eds.; Springer International Publishing: Cham, Switzerland, 2016; pp. 1493–1520. [CrossRef]
9. Leder, S.; Menges, A. Architectural design in collective robotic construction. *Autom. Constr.* **2023**, *156*, 105082. [CrossRef]
10. Ma, Y. The Application of Numerical Control Technology in Wood Processing Equipment. *For. Grassl. Mach.* **2007**, *5* , 31–36. [CrossRef]
11. Yuan, F.; Zhou, J.; Yan, C. Digital Craftsmen: The Future of Architecture in Human-Computer Collaboration. *Archit. J.* **2019**, *4*, 1–8 .
12. Menges, A. *Material Computation: Higher Integration in Morphogenetic Design*; John Wiley & Sons: Hoboken, NJ, USA, 2012.
13. Gramazio, F.; Kohler, M. *Made by Robots: Challenging Architecture at a Larger Scale*; John Wiley & Sons: Hoboken, NJ, USA, 2014.
14. Willmann, J.; Knauss, M.; Bonwetsch, T.; Apolinarska, A.A.; Gramazio, F.; Kohler, M. Robotic timber construction—Expanding additive fabrication to new dimensions. *Autom. Constr.* **2016**, *61*, 16–23. [CrossRef]
15. Albenque, E.; Hudert, M.; Humbert, L.; Weinand, Y. Generation process and analysis of innovative timberfabric vaults. *Struct. Eng. Int.* **2014**, *24*, 254–264. [CrossRef]
16. Pabla, B.; Adithan, M. *CNC Machines*; New Age International: Delhi, India, 1994.
17. Kovacic, M.; Brezocnik, M.; Pahole, I.; Balic, J.; Kecelj, B. Evolutionary programming of CNC machines. *J. Mater. Process. Technol.* **2005**, *164*, 1379–1387. [CrossRef]
18. Zhao, W.; Mey, J.; Schöne, R.; Götz, S.; Aßmann, U. RobotRAGs: A reference attribute grammar-based integration approach for robotic assembly lines. In Proceedings of the 2023 49th Euromicro Conference on Software Engineering and Advanced Applications (SEAA), Durres, Albania, 6–8 September 2023; pp. 22–29.
19. Rossi, A.; Javadian, A.; Acosta, I.; Özdemir, E.; Nolte, N.; Saeidi, N.; Dwan, A.; Ren, S.; Vries, L.; Hebel, D.; et al. HOME: Wood-mycelium composites for CO_2-neutral, circular interior construction and fittings. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2022; Volume 1078, p. 012068.
20. Krieg, O.D.; Menges, A. Potentials of robotic fabrication in wood construction: Elastically bent timber sheets with robotically fabricated finger joints. In Proceedings of the 33nd Annual Conference of the Association for Computer Aided Design in Architecture, Los Angeles, CA, USA, 21–27 October 2013; pp. 253–260.
21. Delgado, J.M.D.; Oyedele, L. Robotics in construction: A critical review of the reinforcement learning and imitation learning paradigms. *Adv. Eng. Inform.* **2022**, *54*, 101787. [CrossRef]
22. Xiao, B.; Chen, C.; Yin, X. Recent advancements of robotics in construction. *Autom. Constr.* **2022**, *144*, 104591. [CrossRef]
23. Felbrich, B.; Schork, T.; Menges, A. Autonomous robotic additive manufacturing through distributed model-free deep reinforcement learning in computational design environments. *Constr. Robot.* **2022**, *6*, 15–37. [CrossRef] [PubMed]
24. Melenbrink, N.; Werfel, J.; Menges, A. On-site autonomous construction robots: Towards unsupervised building. *Autom. Constr.* **2020**, *119*, 103312. [CrossRef]
25. Balaguer, C.; Abderrahim, M. (Eds.) Construction automation and robotics. In *Robotics and Automation in Construction*; InTech: Rijeka, Croatia, 2008 ; pp. 21–42.
26. Leng, Y.; Shi, X.; Hiroatsu, F.; Kalachev, A.; Wan, D. Automated construction for human–robot interaction in wooden buildings: Integrated robotic construction and digital design of iSMART wooden arches. *J. Field Robot.* **2023**, *40*, 810–827. [CrossRef]
27. González Böhme, L.F.; Quitral Zapata, F.; Maino Ansaldo, S. Roboticus tignarius: Robotic reproduction of traditional timber joints for the reconstruction of the architectural heritage of Valparaíso. *Constr. Robot.* **2017**, *1*, 61–68. [CrossRef]
28. Wu, X. Artificial intelligence driven promotion of cultural heritage protection in the context of harmony rural construction. In *Design Studies and Intelligence Engineering*; IOS Press: Amsterdam, The Netherlands, 2024 ; pp. 923–933. [CrossRef]
29. Kromoser, B.; Spitzer, A.; Ritt, M.; Grabner, M. Wooden bridges: Strategies for design, construction and wood species–From tradition to future. *Int. J. Archit. Herit.* **2024**, *18*, 652–668. [CrossRef]
30. Zhao, J.; Agkathidis, A.; Lombardi, D.; Chen, H. Reinterpreting the Dougong joint: A systematic review of robotic technologies for the assembly of timber joinery. In *Architectural Science Review*; Taylor & Francis: Abingdon, UK, 2024; pp. 1–15.
31. Pan, L.; Zhou, M.; Zhuang, H.; Wang, J. Construction forms and seismic performance of the ancient Chinese buildings joined by tenon–mortise joints. *Appl. Sci.* **2022**, *12*, 7505. [CrossRef]