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# A Parametric HBIM Approach for Preservation of Bai Ethnic Traditional Timber Dwellings in Yunnan, China

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**Abstract:** This paper proposes a meta-model-based parametric Historic Building Information Modelling (HBIM) approach to preserving and renewing traditional timber dwellings, specifically focusing on traditional Bai ethnic residential architecture. The study integrates traditional architectural principles with contemporary digital construction techniques. Traditional Bai dwellings have complex timber structural and spatial characteristics with various components. Results from the application of HBIM demonstrate improved efficiency in documenting and managing structural information, facilitating the maintenance and preservation of heritage buildings. The study concludes that HBIM, supported by parametric and generative design approaches, offers significant advantages in the digital preservation of architectural heritage. This approach not only ensures the structural integrity and historical accuracy of the models but also provides a scalable solution for managing and preserving traditional dwellings in the face of modernization pressures. This research broadens the scope of parametric design within digital construction theory, particularly concerning ancient timber structures. It offers a crucial framework that can inform both future studies and practical efforts in the preservation of heritage buildings.

**Keywords:** HBIM; parametric design; generative design; traditional timber dwelling

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## 1. Introduction

As cities grow and more people move to urban areas, the need to develop modern infrastructure and amenities poses significant challenges to preserving culturally important buildings and architectural heritage. With 55 minority groups, Chinese architectural art is rich and diverse. Each of these ethnic architectural styles is not just about the buildings but also about a deeper connection to the environment, traditional culture, and social structure.

Traditional dwellings are of architectural or cultural significance, reflecting the fundamental architectural identities of specific communities. With the implementation of China's rural revitalization strategy, the sustainable maintenance and preservation of traditional dwellings has increasingly attracted academic attention [1,2]. At least three significant issues have been identified in the research of Chinese traditional dwellings preservation. Firstly, traditional architecture with historical, ethnic, and regional characteristics faces issues of heritage loss [1,3]. Secondly, although many architects advocate for the protection and inheritance of traditional residential houses, the regions of ethnic minorities in China are severely affected by the "butterfly effect" with issues of architectural assimilation and homogeneity [4–6]. Last but not least, as most of Chinese historical architectural information is passed down orally and via text records by craftsmen and apprentices [7], preservation and maintenance of traditional dwellings poses great challenges, consuming a great deal of manpower and resources. This problem is further exaggerated by the aging of local craftsmen and the dwindling number of young industry apprentices [8,9].

To shed light on these concerns regarding traditional dwellings, researchers and policymakers are exploring various strategies and tools. One critical focus is the use of advanced technology, particularly Building Information Modeling (BIM), to record, document, and recreate these traditional architectural designs. This approach could offer a practical and robust solution for preserving China's rich architectural history and ensuring its cultural inheritance for future generations. Currently, the BIM approach is renovating the architecture, engineering, and construction (AEC) industry by providing a collaborative and data-rich digital representation of built assets throughout their entire lifecycle. Murphy firstly proposed the concept of Heritage Building Information Modeling (HBIM) specifically for historical buildings [10]. HBIM plays a crucial role in modern maintenance, renovation, and promotion of historical buildings. Through HBIM, the structural, dimensional, and material information of historical buildings can be documented and managed within the model, improving maintenance efficiency [11]. Moreover, it enables the tracking of environmental changes around them, as well as monitoring their deterioration due to aging [12]. HBIM can also be used to develop the virtual and interactive tools based on augmented and virtual reality for historical education using technologies like VR and AR [13–15].

However, on one side, generating a three-dimensional representation of traditional dwellings in HBIM is quite complex. Historical buildings are often intricate, irregular, and large in scale. Historic timber constructions may present even more complex configurations with irregular cross-section elements. This makes generating presentations of such traditional historic building components complicated in the HBIM paradigm. On another side, the intrinsic nature of any dwelling is residential. Due to the change of demands of contemporary living style, traditional dwellings' preservation faces challenges as to their sustainable and effective conservation while maintaining and enhancing their functionality as residences [16,17]. As a result, preserving and renovating these structures requires a certain level of adaptability to align with contemporary lifestyle demands.

Regional historical buildings, such as Siheyuan of Beijing, the Bai-style residences in Yunnan, Fujian Tulou, Hui-style residences, and the stilt houses of Guizhou, hold immeasurable cultural value. Chinese rural revitalization and development is a national strategy, which involves not only improving the economic conditions of rural residents but also preserving and promoting their cultural heritage. As a result, this study aims to provide a design approach that enables effective inheritance of traditional architectural characteristics for traditional dwellings preservation using innovative parametric HBIM based on meta-models.

## *1.1. Relevant Concepts*

### 1.1.1. Parametric Modeling in the HBIM Paradigm

Parametric modeling is a popular 3D modeling technique that has been applied in the restoration and preservation design of traditional dwellings in recent years [18–20]. Parametric design can be defined as an algorithmic process that consists of parameters and rules, which together can define, encode, and elucidate the relationship between the designer's intent and design response [21–24]. It allows designs to be manipulated and altered by changing the values of these parameters and enables the creation of adaptable and flexible models, where changes propagate automatically throughout the design, maintaining the consistency and integrity of the model. Generative design is a step further into the realm of computational design. It combines parametric modeling with algorithms and often artificial intelligence to explore a wider array of design possibilities [25–28]. It automates the creation of design options by utilizing computational power to generate a multitude of design solutions based on specific input parameters and rules set by the architects. Together, parametric modeling relates to the BIM paradigm, as the latter uses

PD's concepts of associative geometry and topological relationships [29] that establish dependencies among different design elements, while generative design informs BIM by contributing innovative and efficient layouts, forms, and configurations for consideration in the detailed model.

In addition, parametric models contain more semantic information than traditional models. They can reflect the structure and function of various parts of a building, facilitating the management of the building. In fact, in recent years, different research groups have explored algorithm-assisted design and its potential applications in cultural heritage through studies in 3D virtual and augmented reality applications. Among these, Grasshopper®, a plug-in for Rhinoceros® software (Version 8), is a visual programming language that has become increasingly popular in recent years. It is not only suitable for project design involving objects or interiors, but also in the preservation of architectural heritage. Existing studies have recognized the advantages of Algorithm-Aided Design (AAD) and the use of Rhinoceros software for traditional Chinese wooden architectures [30–33].

In the field of heritage and historical buildings preservation and protection, parametric modeling is extensively applied and studied. Numerous projects have adopted parametric methods to restore or digitally preserve historical buildings within the paradigm of HBIM. For instance, the French company Ubisoft utilized parametric modeling to reconstruct the Notre-Dame de Paris in a virtual environment, aiding in the restoration of the spire after a fire [34]. Based on measured data from remnants of ancient Greek sites, Microsoft restored the complete architectural scenery of Ancient Greece from two thousand years ago [35].

Another application of parametric techniques for historical buildings preservation and revival is to generate design variants of these buildings while still preserving their heritage characteristics. Here, traditional design principles are encoded as parameters and rules which enable the parametrization process for more efficient redesign or adaptation. Lu introduced a parametric plug-in into ArchiCAD software, adjusting component styles and generating imitation-antique building models based on the design principles of Chinese historical architecture. The work of Wang et al. describes a parametric design approach to generate representation of Chinese courtyard-dwellings Siheyuan [30]. Based on analysis of traditional design principles, they identified five parameters that facilitate generation of an individual building example. The proposed algorithmic tool enables architects to quickly generate accurate 3D Siheyuan courtyard house models by inputting parameters based on traditional design principles, facilitating the preservation of this cultural heritage and enhancing design flexibility. In their study [36], Ding and colleagues examined the research on integrating Building Information Modeling (BIM) with Chinese architectural heritage. They suggest that the digitalization of architectural heritage, combined with the application of BIM technology for managing the entire lifecycle of heritage buildings, could become an emerging trend in the field.

### 1.1.2. Meta-Model

The concept of a meta-model has been widely applied in fields such as information processing, programming languages, and object modeling. A meta-model is a model about models, describing how to build models, the semantics of models, and how models integrate and interoperate. It provides a normative definition of the modeling environment for a particular domain, defining the syntax and semantics of that domain and representing all or most systems within it. Under the same meta-model, users can create specific models within the scope of the meta-model as needed. This shifts the focus from constructing models for specific objects to constructing the meta-model itself. Therefore, after establishing a meta-model for a particular type of building, the automatic modeling of that type of building can be quickly achieved.

Meta-models play a crucial role in supporting modeling and design within numerous sectors such as software engineering, information management, and knowledge representation [37]. In the field of BIM, meta-models serve to define the objects in architectural models by detailing their attributes, relationships, and behaviors. This enables the transformation of models into formats that can be computationally interpreted, supporting thorough management, analysis of architectural models, and coordination of diverse construction endeavors. Various fields including computing, urban monitoring [38], building energy efficiency, and industrial design have witnessed applications of meta-modeling methods for enhancing simulations. Despite its widespread application, the sphere of architectural heritage conservation sees limited research on meta-methods. Nonetheless, García-Macías has introduced a novel meta-model specific to historical masonry damage recognition, diverging from conventional Structural Health Monitoring (SHM) methods, and targeting improvement in large-scale simulations [39]. In the emerging smart era, metadata, characterized as a structured descriptive language, holds potential in processing data related to architectural heritage models, thus facilitating the extraction of valuable insights from architectural heritage.

### 1.1.3. Bai Ethnic Residences and Historical Cultural Architecture

The Bai ethnic group primarily resides in the Dali Bai Autonomous Prefecture in Yunnan Province. This area, designated as a national nature reserve and esteemed for its scenic allure, has emerged as a popular tourist destination [40]. Figure 1 shows the location of Xizhou ancient town, one of the most famous Bai traditional villages in Dali area. The Bai people have created a unique ethnic culture, and Bai ethnic residences are an important part of Bai culture and Chinese historical cultural architecture.

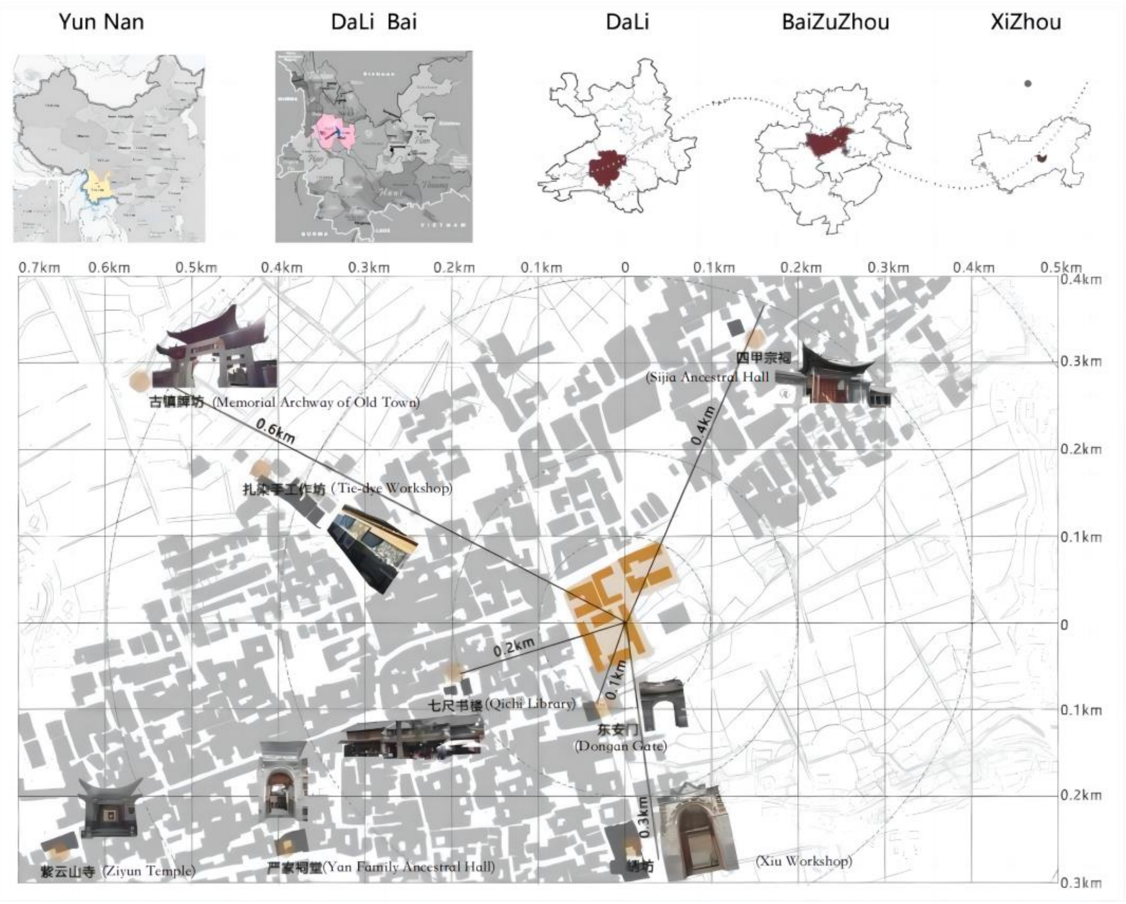


**Figure 1.** Location analysis of Xizhou ancient town.

As vital elements in cultural inheritance, residential buildings often show local usage, craftsmanship, and spiritual values. Bai ethnic homes not only fulfill everyday functional needs as familial gathering spots, but their construction, decoration, and craftsmanship also provide physical representations of intangible cultural heritage. These architectural structures are diverse in form and distinct in character, with deep connections to economic, cultural, and geographic aspects [41]. Thus, traditional Bai residential buildings embody both material and spiritual elements, making their cultural value extraordinarily significant. Once lost, these structures cannot be replicated.

The types of Bai ethnic dwellings are extremely diverse. Since the Neolithic period, various building types, such as semi-subterranean and stilt houses, have appeared. The existing Bai dwellings are greatly influenced by Han architecture tracing back to the Ming Dynasty [42,43]. With the continuous evolution, integration, and development of society, the layout, structure, and decoration of Bai dwellings exhibit unique characteristics, which will be extensively introduced in Section 2.1.1 Meta-Object.

### 1.2. Research Framework and Contributions

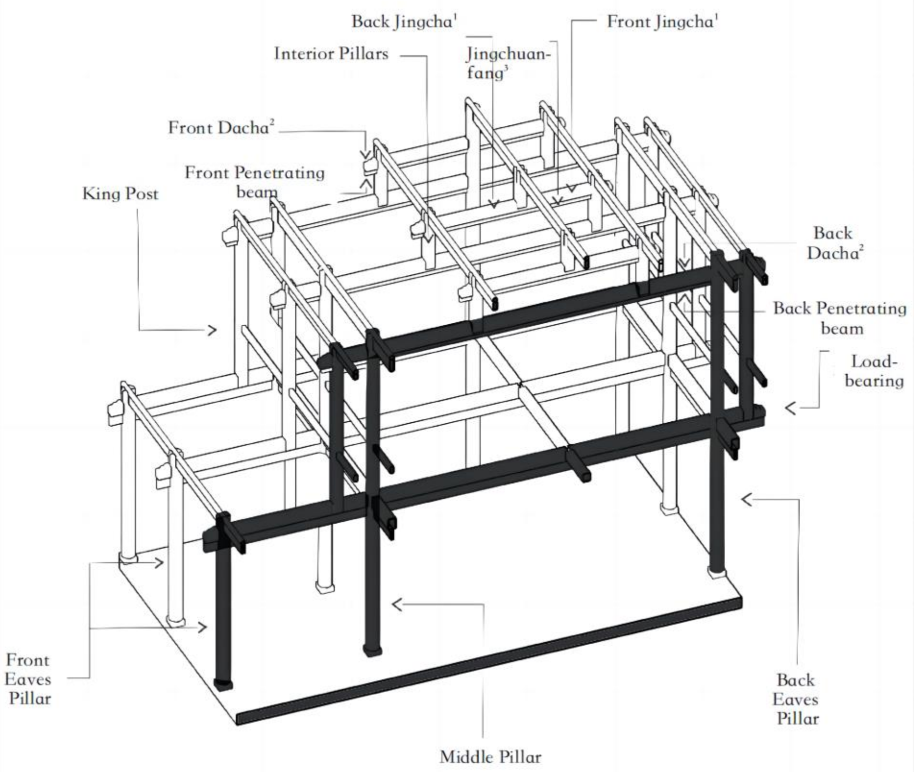
In this study, we focus on traditional Bai ethnic dwellings and introduce an innovative parametric modeling approach utilizing a meta-model for intricate timber structures within the HBIM framework. Timber structures, often comprising hundreds of components within individual historical buildings, are a common architectural feature in historical cultural buildings. Figure 2 presents a typical two-story timber structure of a Bai ethnic dwelling, where the timber structure complex may be associated with thousands of architectural components of varying sizes. Given the distinctiveness of such historical constructions, precise matching of each component during restoration is crucial. This can be achieved by meticulously defining their geometric and structural properties and coding them using parametric modeling derived from a meta-model. This necessitates a single digital medium that can integrate all building-related information into a 3D model, ensuring the exchange among different "participants" involved in the preservation and management of the building [44,45].

Thus, after analyzing the construction techniques and typological characteristics of Bai ethnic residences, we develop a meta-model generation algorithm in Grasshopper that sums up the architectural features and rules of the structural composition. This method can be utilized for the preservation and renovation of timber structures, thereby improving the sustainability and efficiency during architects' 3D modeling. The development of this program consists of two phases:

(1) Initially, a generation algorithm is created to replicate basic component units forming simple and complex structures (such as pillars and beams).

(2) By classifying and coding common nodes and component elements within these structures, the algorithm proposed in the first phase is further strengthened at the data management level.

Given regional cultural variations, different types of timber construction possess their unique features. In architectural production, it seems implausible to apply a "replicability" method that is suitable for thousands of cases, as with classic production chains, nor is it possible to view architecture as starting from a prototype that allows mass replication of the same outcomes. In fact, this new field involves the design process and heritage management methods rather than the "content" in terms of cultural and formal values. For instance, existing building-related surveys and document preparations, or traditional surveying techniques or the use of innovative survey technologies, such as point cloud techniques and thermal imaging, consider the architectural model as a complex "box", where proper accessibility and performance levels must be ensured. Therefore, professionals can use the structured database combined with HBIM to analyze, strategize, and maintain and, if necessary, intervene in the physical space or its intended use in a rapid and flexible manner. Indeed, due to the implementation of a universal digital platform based on digital model interoperability, it will be possible to design and implement the reconfiguration of architectural structures more quickly than in traditional timelines. This aspect is also related to the perspective of architectural renewal [46], where construction sites can be organized according to the functions of the building, thus achieving an integrated approach to design, construction, and management, and contributing to the heritage and preservation of regional historical cultural architecture.



Note:
1. Jingcha (京插) is called Wujialiang (五架梁) in official Qing dynasty architectural terminology, meaning a beam that spans five purlins;
2. Dacha (大插) is called Qijialiang (七架梁) in official Qing dynasty architectural terminology, meaning a beam that spans seven purlins;
3. Jingchuanfang (京穿方/枋) means the penetrating beam crossing interior pillars.

**Figure 2.** A typical two-story timber structure of a Bai ethnic dwelling.

The results indicate that this method can quickly achieve precise three-dimensional timber components, and the system contributes to the research and management of the entire lifecycle of heritage buildings, providing sustainable possibilities for regional historical cultural architecture.

## 2. Materials and Methods

In response to the deficiencies above during establishing information models for traditional timber architecture, this method proposes an automatic modeling algorithm based on meta-model theory and construction logic. Specifically, this algorithm uses the meta-model theory as a framework and the construction logic of timber architecture as the algorithm logic. The efficient automatic modeling based on meta-models is achieved following a process of "construction logic analysis—spatial topological relationship—programming algorithm generation". As shown in Figure 3, the proposed method includes the following steps:

Step 1: To establish a meta-model framework for traditional timber architecture, covering meta-objects, meta-attributes, meta-relationships, and meta-methods;

Step 2: To extract the construction logic of traditional timber architecture to determine component classification, spatial relationships, and assembly sequence;

Step 3: Based on the timber construction system logic, to establish a meta-model by first determining meta-objects and meta-attributes, then establishing the spatial topology of components, and finally constructing the meta-model using modeling software;

Step 4: To utilize the meta-model and survey data for automatic modeling to construct an information model of traditional timber architecture.

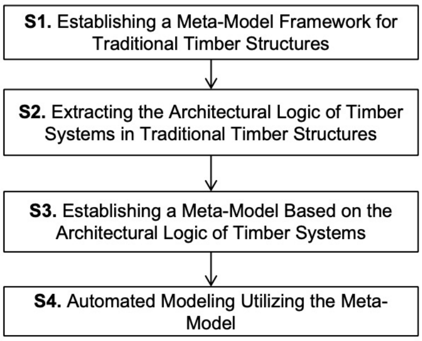


**Figure 3.** Procedures for establishing an automatic Building Information Modeling method based on meta-models and construction logic.

This method provides a fast way to construct an accurate BIM of traditional timber construction, recording construction techniques with adjustable precision. Figure 4 presents the conceptual framework of this study. Within this framework, meta-objects refer to the various components (constitutive objects) of the timber system, while meta-attributes pertain to the sematic properties. Both of the above can be obtained from conventional architecture research and practices. Meta-relationships and meta-methods are grounded in the architectural logic of the timber system. Meta-relationships define the interrelationships between the different components (spatial and numerical modeling relationships), while meta-methods are the procedures for modeling the components into the timber system (methods by which various components are combined into the structural system under certain constraints and control conditions). Consequently, to establish a meta-model for timber architecture, one must not only determine the meta-objects and meta-attributes but also adhere to Step 2 in Figure 3, to analyze and summarize the construction logic of the traditional architectural timber system.

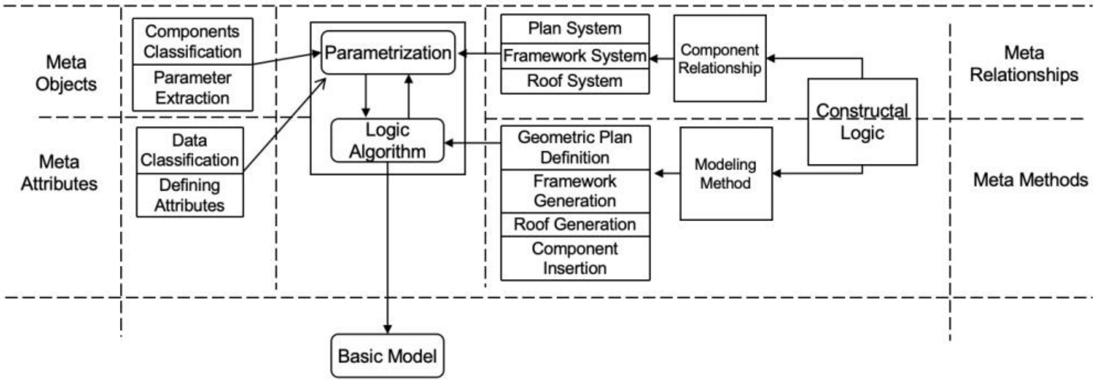


**Figure 4.** The conceptual framework of the meta-model.

## 2.1. *The Meta-Model of Traditional Bai Ethnic Dwellings*

This sub-section introduces the initial phase of work, including the analysis of the form and structure of traditional Bai dwellings and appropriate parameter transformation of the structural features of our research object. It is essential to note that the goal of continuous modeling is to replicate a large volume of different types of large timber components, starting from simple point–line–face connections and moving to complex interlocking (e.g., mortise and tenon joints).

Figure 5 shows the constitution of the meta-model in this study. Meta-object is a generic term used in meta-modeling languages to define all elements within a model. These can be concretely represented by timber components such as beams, pillars, and lintels or abstractly represented as meta-properties, meta-relationships, or meta-methods. A meta-attribute pertains to general properties used during modeling, including size, area, volume, construction type, material, and component number. Meta-relationship describes the ways in which meta-objects interact, focusing on spatial and numerical connections between different elements. Meta-methods detail the assembly processes of meta-objects, explaining how various components are combined into a coherent structural system under specified constraints and control conditions [39].

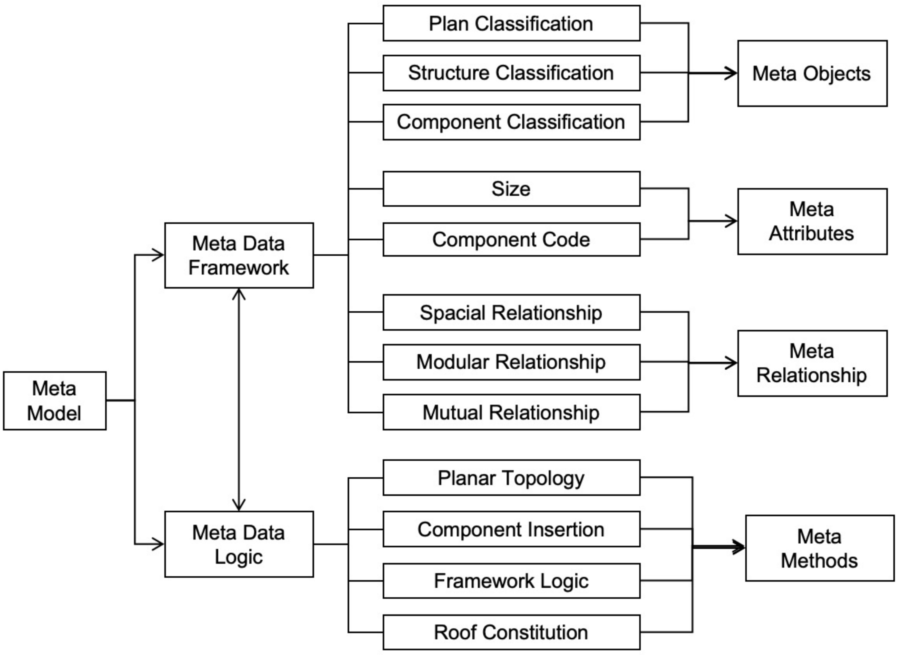


**Figure 5.** Constitution of the proposed meta-model.

By establishing a modeling framework based on a meta-model, this implementation addresses the challenges of information modeling in traditional timber construction. It transitions from modeling specific objects to meta-model building, thereby enabling rapid, automatic modeling of architecture with numerous unique features.

### 2.1.1. Meta-Object

(1) Plan type

The "fang" ("坊") is the basic and distinct architectural unit within a larger building complex in a typical Bai ethnic dwelling. It commonly comprises four beam frames and a front veranda on the ground floor, creating three rooms across two stories and a typical depth of two rooms (Figure 6). The main "fang", which can vary from one to three rooms in width, usually has attached side rooms on both the left and right. These side rooms are considered as auxiliary spaces. They are usually aligning with the back eave wall of the main section, but with reduced depth, bay spacing, width, and height. This configuration contributes to architectural diversity by creating varied roof elevations and a spatial volume that is higher in the main area and lower in the auxiliary areas, enhancing the overall architectural profile.

In traditional Bai dwellings, courtyards are formed with either a single "fang" unit or multiple "fang" units, together with other architectural elements such as a screen wall. With various configurations and layouts, the concept of "fang" enables the creation of diverse and adaptable courtyard spaces to meet different living requirements. Typical traditional Bai ethnic residential structures include single "fang", double "fang", triple "fang"' with a screen wall (also referred to as "three rooms and a screen wall" or "three rooms and a wall screening"), quadrangles with five courtyards (Also refer to "four houses and five courtyards”), and multiple courtyards. Table 1 shows the planar and 3D features of the selected Bai dwellings.

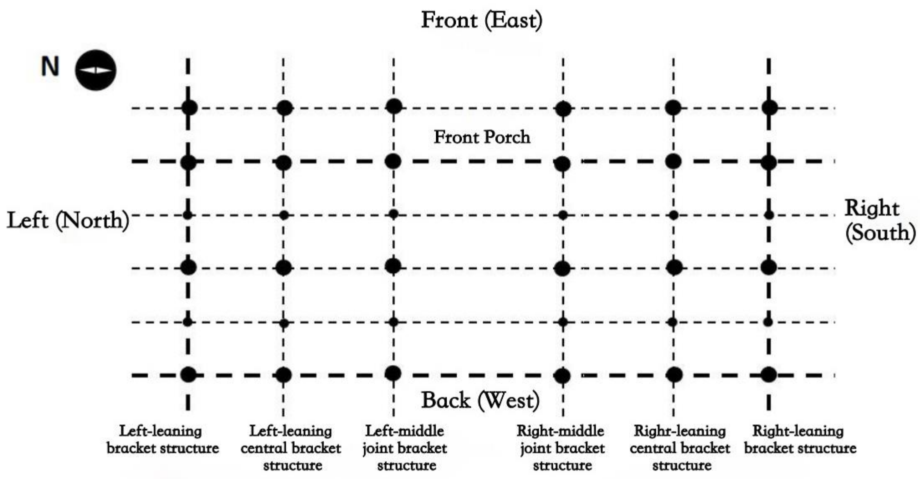


**Figure 6.** Plan axis characteristics of individual “fang”.

**Table 1.** Planar and 3D features of representative Bai dwellings.

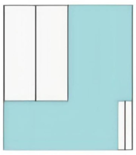
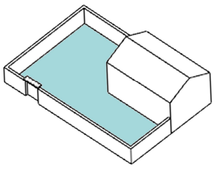
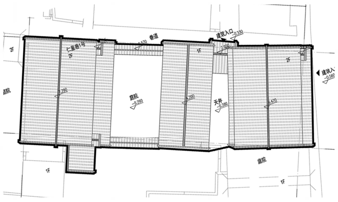
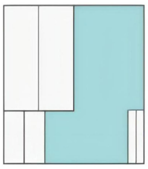
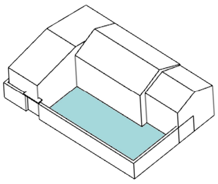
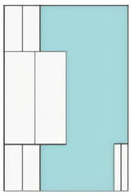
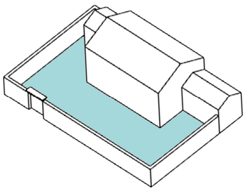
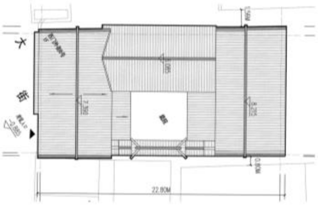
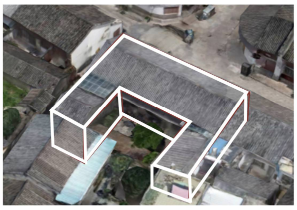
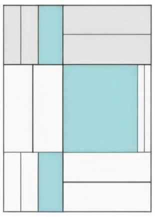
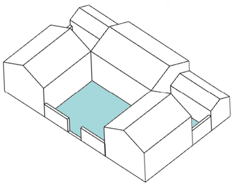
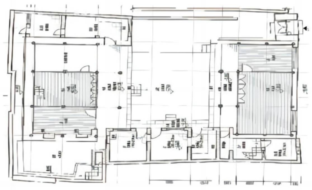
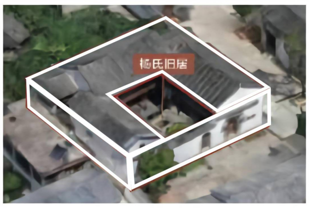
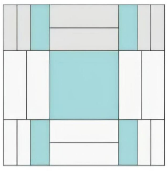
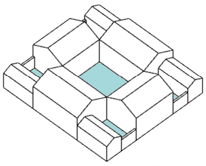
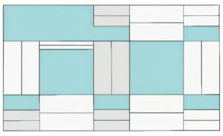
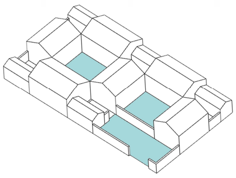
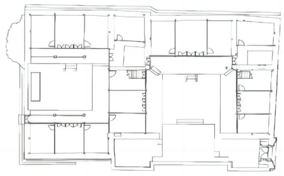
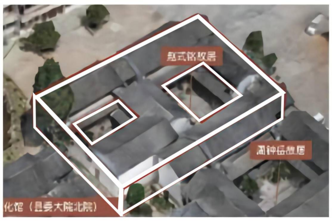
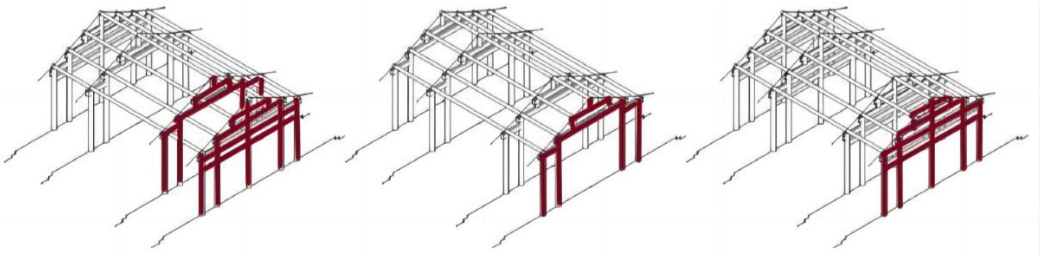
| Name | Graphic Prototypes | Planar 3D Model | Floor Plan | Aerial Photography |
|---|---|---|---|---|
| Xukexia’s Courtyard |  |  |  |  |
| Gao’s Courtyard |  |  |  |  |
| Pan Zhao’s Former Residence |  |  |  |  |
| Shiming Zhao’s Former Residence |  |  |  |  |

**Table 1.** *Cont.*

| Name | Graphic Prototypes | Planar 3D Model | Floor Plan | Aerial Photography |
|---|---|---|---|---|
| Zhou's Former Residence |  |  |  |  |
| Yang's Former Residence |  |  |  |  |

(2) Structural Type

Adaptive to regional climate, material resources, and building customs, traditional Bai ethnic residential architectures have evolved into three categories of timber-frame structures: "penetrating and interlocking framework" (chuandou 穿鬥), "interlocking and lifting beams" (擡梁 táiliáng), and a mix of the above two as illustrated in Figure 7. The timber-frame structure involves using pillars and beams as the main structural components. The weight of the house is transferred from the beams to the pillars and then to the ground, with walls serving primarily as enclosures.



Hybrid framework    Interlocking and lifting beams    Penetrating and interlocking framework

**Figure 7.** Three structural types of traditional Bai ethnic dwellings.

(3) Component Types

i. Pillars: These are vertical load-bearing components and are one of the main elements of a building. In traditional architecture, there are many types of pillars categorized by their position and function, and accordingly named, shaped, and constructed.
ii. Beams: These are the primary load-bearing components in traditional structural frameworks, supporting all the weight of the structural components and the roof. They are the most crucial and critical parts of the upper framework. Depending on their position, function, and shape, they have different names and constructions, including seven-frame beams, five-frame beams, three-frame beams, top beams (lunar beams), embracing beams, and load-bearing beams.
iii. Tie beams: These components stabilize the connection between pillars and beams. There are many types of lintel components.
iv. Purlins: These are among the most basic components in traditional architectural timber structures. Purlins directly bear the roof load and transfer it to beams and pillars. In Yunnan, purlins refer to both "Heng" (桁) and "Lin" (檩) in local architectures.

Table 2 presents example images of the timber construction elements in Bai traditional dwellings.

**Table 2.** Classification of large wooden structural components.

| | | | | |
|---|---|---|---|---|
| **Survey of Timber Construction Elements** | **Beam** |  |  |  |
| | | **Straight Beam** | **Lunar-shape Beam** | **Straight Beam** |
| | **Pillar/Column** |  |  |  |
| | | **Gable Pillar/Column** | **Ridge Pillar/Column** | **Eaves Pillar/Column** |
| | **Purlin** |  |  |  |
| | | **Purlin 1** | **Purlin 2** | **Purlin 3** |
| | **Tie Beam** |  |  |  |
| | | **Tie beam component** | **Penetrating tie beam component** | **Bracket component** |

### 2.1.2. Meta-Attributes

(1) Plan Dimensions

Based on survey drawings, the depth of the main hall dwelling is about 4.6–5.2 m, with a width of 3.2–4.25 m. Some standard combinations are evident, such as a width of 3.7 m with a depth of 5.1 m and a width of 3.9 m with a depth of 5.2 m. The ratio of width to depth is generally between 0.7 and 0.8, roughly rectangular. The width of the rooms on either side of the main room is slightly narrower than the main hall. Figure 8 shows the dimensional relationships between types of rooms in a typical single-courtyard complex.

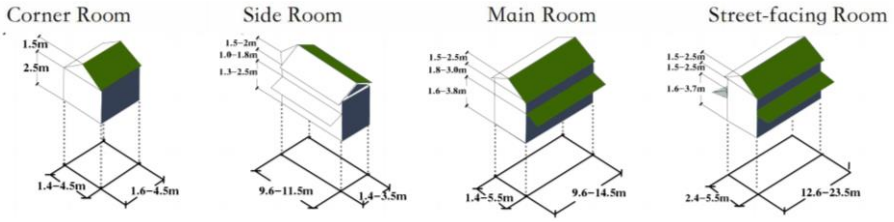


**Figure 8.** Dimensional relationships of different types of rooms in a single-courtyard complex.

(2) Facade Dimensions

The relationship between the timber frame and the depth of the main hall: if d represents half the depth of the main house, c the distance between two pillars in the roof framing, and A the distance from the main beam to the top of the pillar in the roof, then this relation can be established in the diagram: c = d/2; A = c × roof pitch (which is matched based on the depth of the house, and it will be described in detail how different roof pitches are adopted depending on the depth of the house) = d/2 × roof pitch. The so-called "pitch" refers to the ratio of the total height of the roof to half the depth of the main structural frame. Specifically, the height from the central beam to the front (rear) eave beam compared to the distance between the ink hearts of the front (rear) eave pillar and the central pillar usually falls between 0.45 and 0.5, 0.5 being five pitch and 0.45 being four and a half pitch. This concept essentially employs the ancient Pythagorean theorem in architecture, treating the roof as a simple mathematical model comprising an isosceles triangle with a common right-angle side formed by two identical triangles. Figure 9 summarizes the façade dimensions of a timber structure of a typical traditional dwelling.

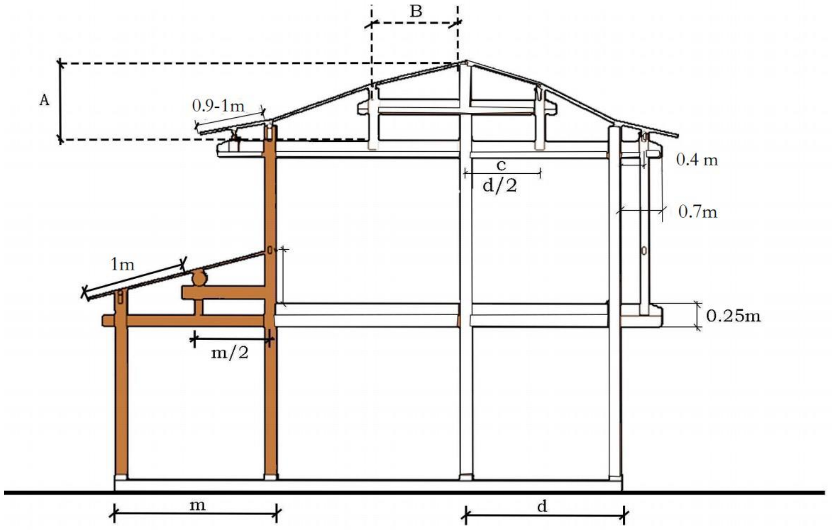


**Figure 9.** Facade dimensions of a timber structure of a traditional dwelling.

(3) Component Dimensions

The width of beams can be categorized based on the size and grade of the residence (Table 3):

Beams: 0.1–0.3 m in width, 3–9 m in length
Pillars: 0.22–0.3 m in diameter
Purlins: 0.1–0.2 m in width, 3–9 m in length
Tie Beam: 0.1–0.2 m in width, 3–9 m in length

**Table 3.** Selected standard components.

| Components | Model | Size |
|---|---|---|
| Beam |  | W:100–300 mm<br>L: 300–9000 mm |
| Pillar/Column |  | W: 220–300 mm<br>L: 300–13000 mm |

**Table 3.** *Cont.*

| Components | Model | Size |
|---|---|---|
| Purlin |  | W:100–200 mm<br>L: 300–9000 mm |
| Tie Beam |  | W:100–200 mm<br>L: 300–9000 mm |

### 2.1.3. Meta-Relationships

#### (1) Planar Relationships

The plan layout based on the "square motif" evolves into various rectangular topologies, presenting a square and orderly spatial form. The horizontal base plane corresponds one-to-one with the space, controlling the spatial form's characteristics, with the spatial form being an overt expression of the horizontal base plane. The relationship is shown in Figure 10.

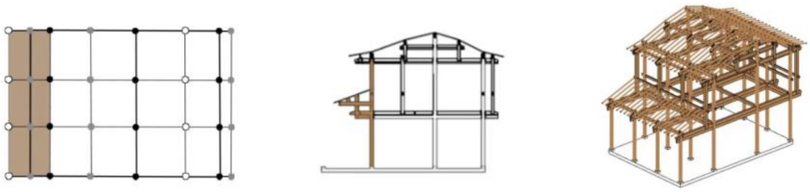


**Figure 10.** A diagram showing the relationship between planar topology, elevation, and three dimensions model.

#### (2) Structural Relationships

The connections in timber framing include hanging, hooping, and threading. From the diagrams (Figure 11), it can be seen that such connection methods align with principles of mechanics: vertical components are joined using "hanging" based on the physical properties of the wood, and "hooping" is used when vertical component nodes are connected to longitudinal structures. For connections between vertical and horizontal structures, "threading" is employed.

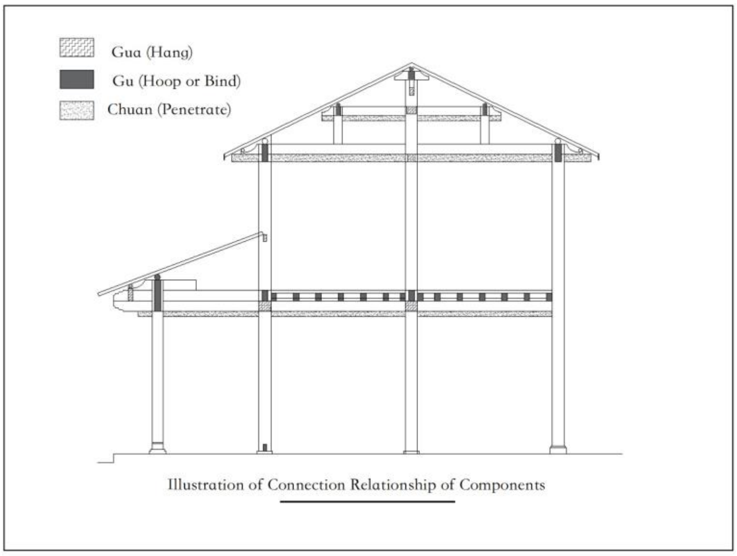


**Figure 11.** Illustration of connection relationship of components.

(3) Component Relationship

Due to the common use of a rectangular layout in Bai architecture, the entire structural system is divided by intervals and composed of pillars and beams, forming a beam–pillar combination. The main depth of Bai residential buildings is generally five bays. Considering that the area is prone to earthquakes, a central pillar has been added to each curved frame. At the same time, the first floor has corridors or eaves, and the second floor has overhangs or hanging pillars. In Bai residential architecture, the beam–pillar framework consists of erecting four large pillars on the ground and using beams to construct the house on top of the pillars; the horizontal timbers at the front and back are the transoms, while the vertical timbers on the left and right are the beams. Overall, Bai residential architecture has a relatively mature structure and a harmonious and unified framework. The depth dimensions of each house are similar and have become a well-suited structural form for the local environment. Figure 12 illustrates the connections between components in a typical Bai residential building.

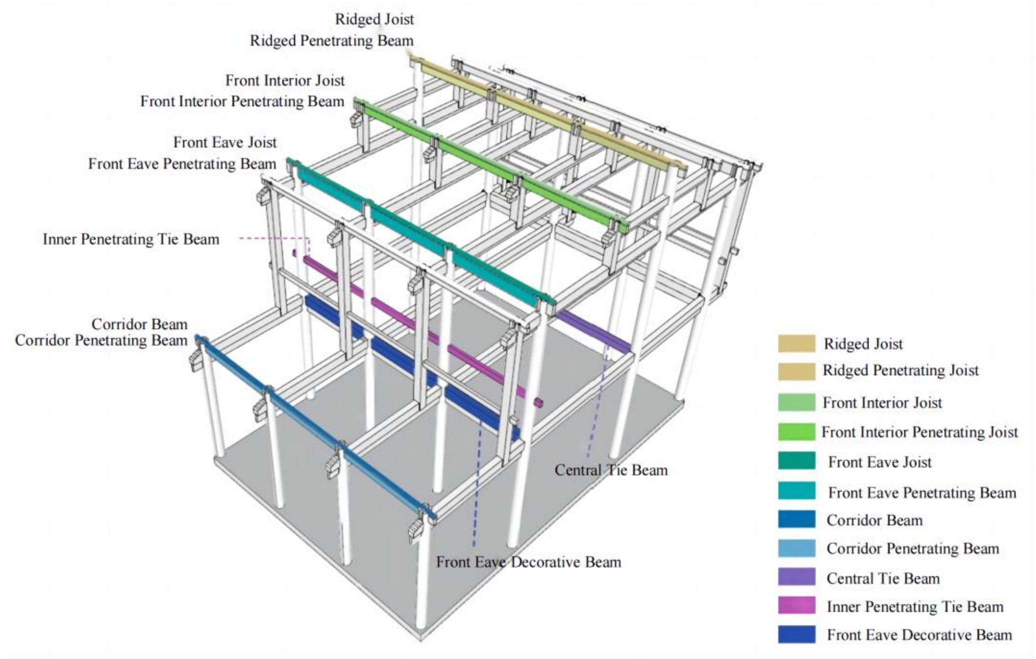


**Figure 12.** An illustrative diagram of the connections between components.

## 2.2. Construction Logic

While traditional timber constructions manifest in diverse forms and have intricate architectures, they share similarities in the materials used, processing techniques, and methods of construction. This allows evolution of various timber architectures to a steady pattern of construction logic over a long period of development. The construction logic of timber structures determines the classification of components, spatial relationships, and the sequence of assembly, and ultimately defines the appearance of the buildings and their building information models. Therefore, by extracting the construction logic of a certain type of building, it is possible to move away from descriptive modeling methods and establish generative meta-models based on the construction logic.

### 2.2.1. The Construction Logic of Traditional Timber Structure Systems

(1) Component Classification and Spatial Relationships

The timber folk buildings are diverse and often exhibit strong regional characteristics. In addition, their structural forms and construction methods display unique construction logic. The meta-model divides the building structure into three sections: roof, building body, and base. The entire architectural system of Bai ethnic residences is divided into four parts: the roof system, framing system, veranda system, and base system. Details of this system is shown in Figure 13. This division is clear and straightforward, and it is commonly applied to timber constructions that use actual size measurements.

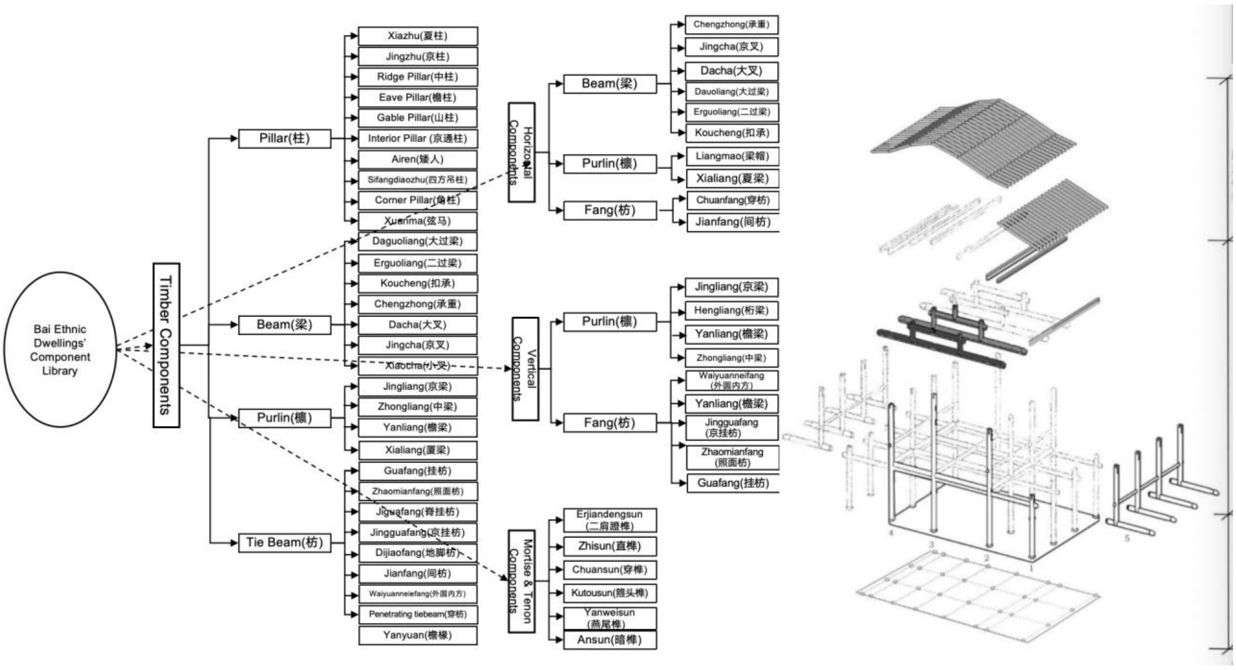


**Figure 13.** Components classification and spatial relationship.

(2) Assembly Sequence

The construction logic proceeds from a one-dimensional identification system to the fabrication of vertical components, then through the creation of horizontal components to restore to a two-dimensional framework, and finally, the completion of the three-dimensional framework. By superimposing multiple combinations onto one framework and adding components, an assembly-type historical and cultural building can be formed (Figure 14).

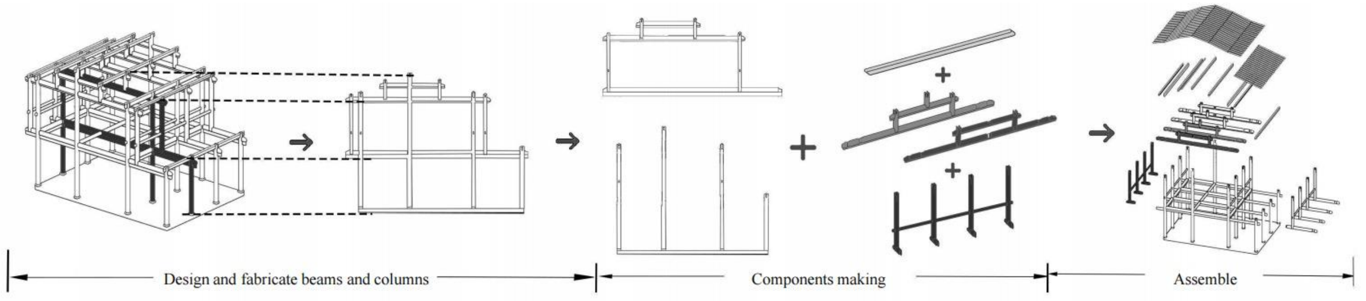


**Figure 14.** Diagram of construction logic combination sequence.

### 2.2.2. Design Logic

In timber constructions built using actual size measurements, the design logic specifically involves:

(1) Determine the spatial node positions based on topological relationships.

(2) Based on the nodes, determine the pillar positions on the plan and the length of the eave pillars.

(3) Based on the intersecting position information of the pillars and beams, determine the position and length of the first layer of beams.

(4) After determining the beam frame assembly, find the spatial position information of the purlins on the first layer based on the plan topology.

(5) Identify the intersection point information between the purlins and the beam–pillars, confirming the position information and length of the purlins.

(6) Locate the spatial position information of the first layer's beams and purlins, and place the spatial information and length of the rafters below the beams and purlins.

(7) Similarly, determine the spatial information and length of the beams and purlins for the second layer.

(8) Find the spatial position information of the second layer's beams and purlins, and insert the spatial information and length of the rafters below them.

(9) Finally, complete the design logic assembly of the entire timber frame structure (Figure 15).

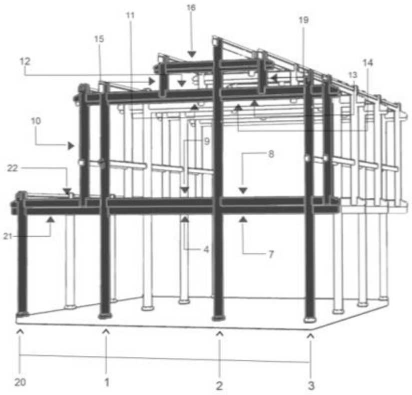


**Figure 15.** Building construction sequence/logic.

The construction logic for timber buildings constructed with actual measurements specifically involves reducing the building's three-dimensional information to a sequence number proportionally. Based on the sequence number on the image, assemble layer by layer from inside to outside, from bottom to top, completing the first frame assembly. Then, after completing multiple frame assemblies, intersperse purlins and rafters into each frame assembly until the entire three-dimensional framework is assembled. Figure 16 illustrates the forward design logic in this subsection.

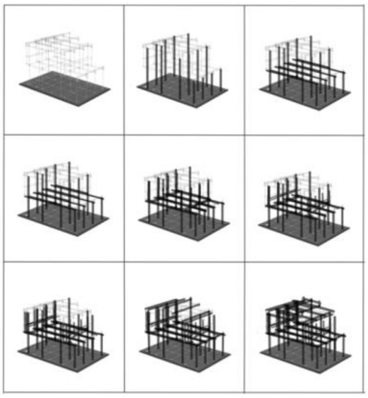


**Figure 16.** Forward design logic.

### 2.3. *A Meta-Model Based on Timber Construction System Logic*

In the process of establishing the meta-model, viewed from the timber construction system's architectural logic which uses actual size building techniques, the grand framework's meta-relationships are divided into three controlling systems: the plan system, the framework system, and the roof system. These three controlling systems determine the interrelationships of all components.

Based on these three controlling systems, the spatial topological framework is established following actual measurement construction logic in the following four steps:

(1) Determination of the plan system: This involves establishing the grid relationship formed by the positions of pillars on the XY-axis and on the Z-axis.

(2) Generation of the framework system: The framework is based on the spatial pillar grid, with beams and purlins intersecting with the pillar grid to form a single group spatial line grid. This line grid forms a repeatable structural unit. In creating the meta-model, conceptualize pillars, beams, and purlins as three types of lines that are mutually perpendicular. Construct a basic framework combination of these three lines to replicate the geometric intersection relationships within the framework to achieve the timber architecture's structural body.

(3) Component placement: Based on the spatial topological framework and using the structural logic and spatial relationships, place all major timber components including pillars, beams, purlins, and rafters using a visual programming algorithm (Figure 17). The logic of steps (1) to (3) is implemented as a single-thread spatial positioning system through visual programming. This system then serves as the spatial topological framework for all components in the timber construction system.

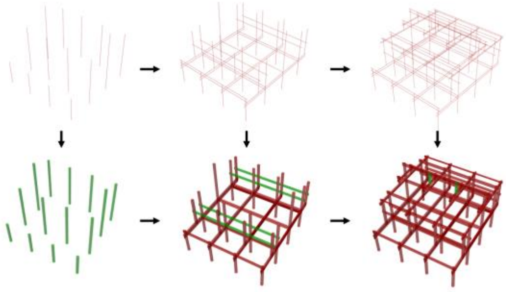


**Figure 17.** Illustrative example of procedure in building meta-model space topology.

(4) Generation of the roof: The roof at the uppermost part of the timber structure is primarily supported by hanging beams and rafters, forming a relatively independent framework (Figure 18). Based on the plan form, establish reference points, and at these reference points, place the rafters and beams to complete the roof assembly.

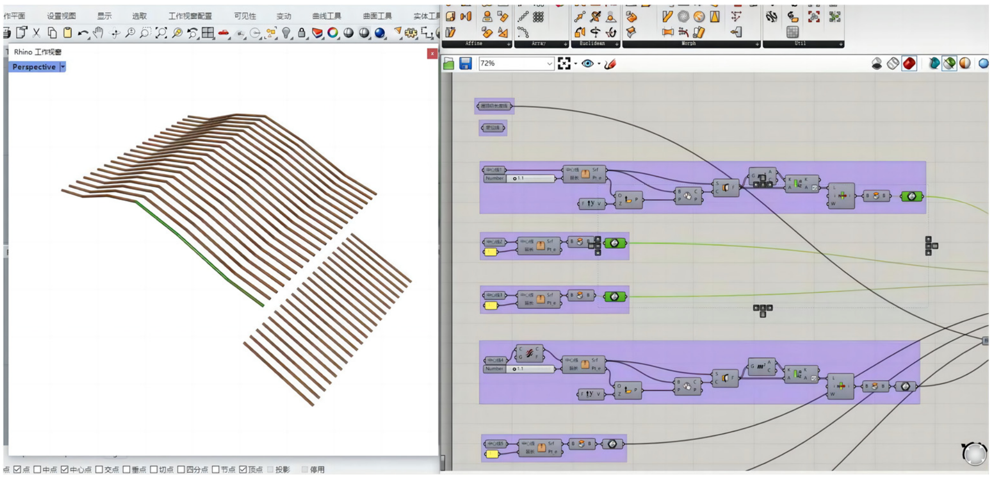


**Figure 18.** Meta-model roof generation system.

## 2.4. Automatic Modeling Based on Meta-Model

Although the courtyard residences vary across different regions of China, they share similarity in terms of generality and construction logic [47–49]. Several existing studies have successfully applied geometric parameterization for traditional Chinese residential timber structures. As introduced in the previous section, beams, pillars, purlins, and rafters are fundamental components in Chinese timber architecture. Their design is based on three types of framing systems: interlocking and lifting framework, penetrating and interlocking framework, and a hybrid one. By altering just a few variables, one can determine the type of framing and the possibilities for various assemblies. Figure 19 illustrates one example solution using our proposed method.

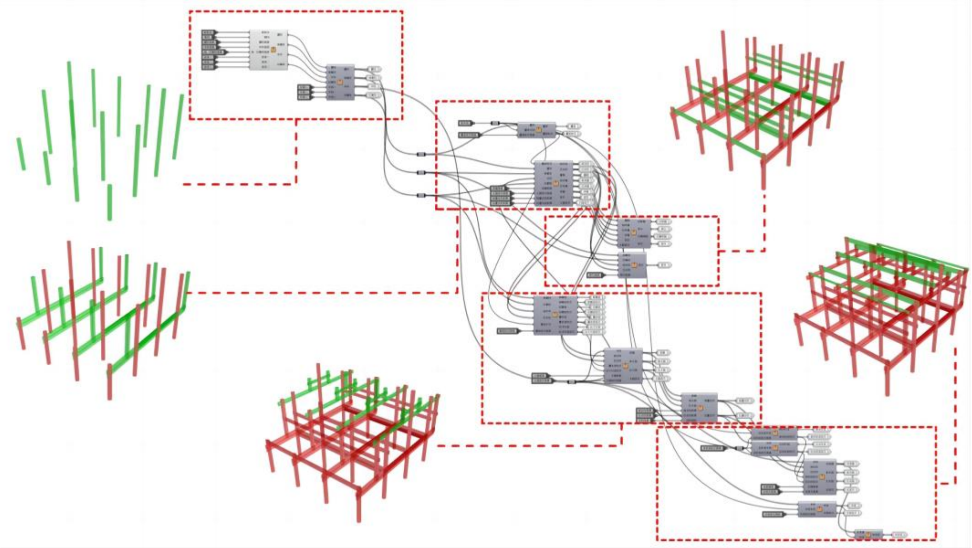
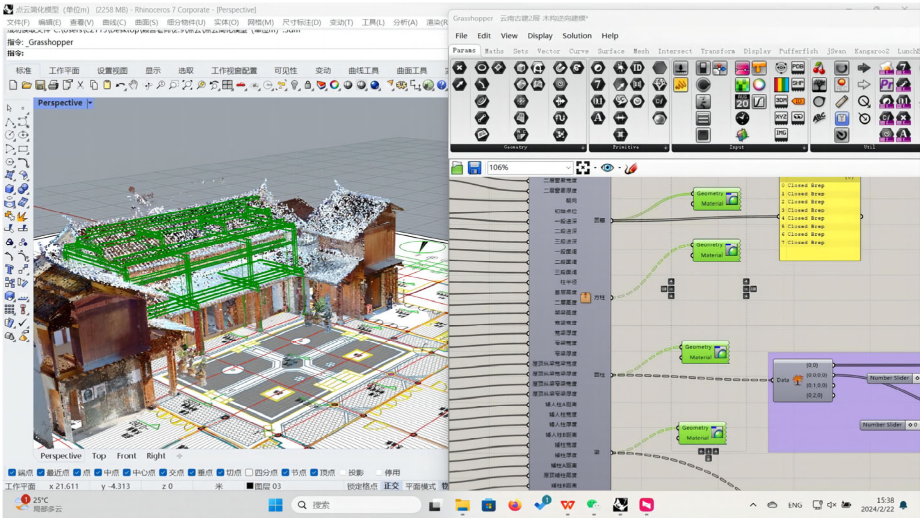


**Figure 19.** The proposed solution. Parameters are displayed in green, and command groups are linked to the corresponding 3D modeling stages. The sequence is as follows: the preliminary algorithm for generating basic elements, adhering to the characteristic features of each component type and construction logic, from columns to beams, then to purlins, followed by the construction sequence of the second layer of beams and purlins, combining the traditional construction logic with the modern coordinate system's algorithm along the Z-axis, X-axis, and Y-axis.

Parameters are then imported into the meta-model and various components are sequentially loaded. Components are adjusted according to the point cloud model, and, once complete, the modeling software can automatically generate the building information model of the traditional timber structure. An illustrative example of the resulting model is shown in Figure 20.



```
0 Closed Brep
1 Closed Brep
2 Closed Brep
3 Closed Brep
4 Closed Brep
5 Closed Brep
6 Closed Brep
7 Closed Brep
```

**Figure 20.** Diagram of the fusion and matching of point clouds and meta-models, where combining with meta-models facilitates the reverse modeling of point clouds.

## 3. Discussion on Result

The proposed method, especially when under the HBIM environment, brings new opportunities for the design and management of restoration projects. First, one of the notable advantages of this method is the efficient parametric modeling of complex cultural buildings. There are six forms of facade for the Bai ethnic hybrid dwellings. They are usually two floors in height and exhibit 12 types of floor plan topologies, as shown in Figure 21.

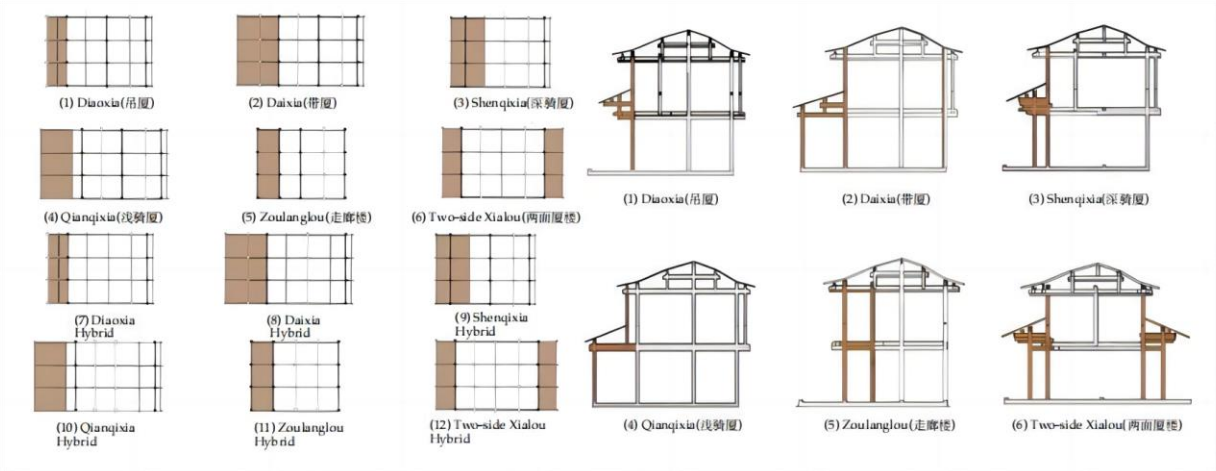


**Figure 21.** The 6 types of elevation forms for hybrid Bai ethnic dwellings and 12 variations in planar topological patterns.

Secondly, with a small set of geometric and typological data from various surveys, the algorithm can rapidly construct models of timber dwellings of various shape and size. In addition, it can also accurately capture the details, including differences in bays and heights. Regarding the 12 different floor plan topologies and 6 facade forms, this algorithm can be used to adjust the height of the columns, the length of the projections, and the size of the recesses, for generating different parametric structures (Figure 22).

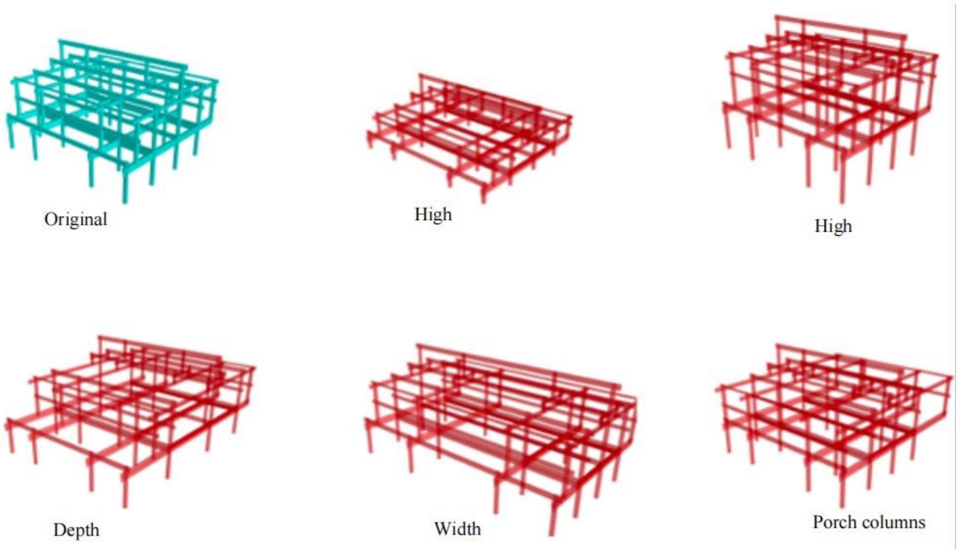


**Figure 22.** Models in the process of component parametrization. The length, width, and height dimensions of columns, beams, and purlins can be changed individually or collectively.

Moreover, to accurately analyze the impact of different parameter frameworks on structural performance, especially from the perspective of reinforcement and maintenance, adjustability of parameters is particularly important. Prior studies have shown that different architectural structures have a significant influence on the roof's load-bearing capacity [50–52]. Additionally, by using "fang" as basic units (such as wooden frame structures) for modular expansion based on the six topological forms of Bai ethnic residences, and combining modular elements by "fang", the components of individual "fang" can be cataloged in the BIM family library, enabling replication possibilities in various environments (e.g., Figure 23). This approach to modeling can be used for successive numerical finite element analysis or in Building Information Modeling. HBIM methods allow modeling using object families; each BIM project consists of well-defined components such as walls, windows, doors, etc. These families can be very basic, requiring only manual modification of the necessary information, or can be extremely complex and detailed, with data that are automatically calculated. Bai ethnic residential architecture includes not only flatland types but also water-friendly and mountain types, with various structures adapted to different environments. To the best of our knowledge, no parametric design method has been suitable for all types of Bai ethnic residence architecture that can replicate its complexity, which highlights the necessity of conducting proper surveys and records.

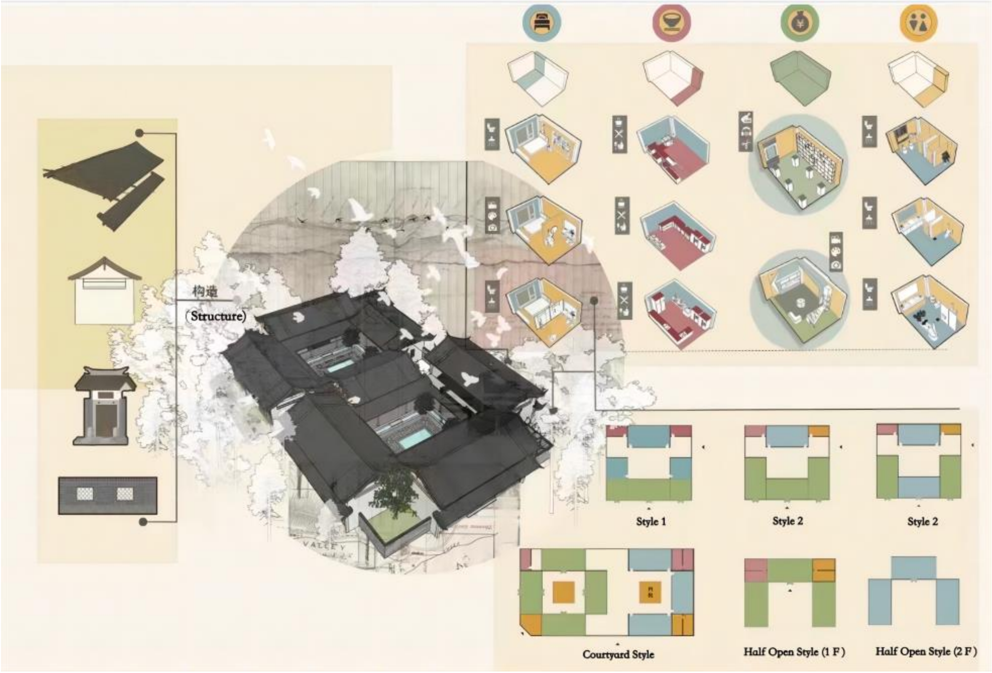


**Figure 23.** The parameterized BIM component library where spatial and functional layouts can be defined.

The theoretical and empirical foundations of this discussion are being applied to the assessment and restoration intervention projects in Xizhou ancient city. With the proposed algorithm, it is possible to rapidly create three-dimensional models of wooden structures with different structural features, such as an interlocking and lifting beams framework, penetrating and interlocking framework, hybrid style, and roofs with bracket sets. Therefore, by combining basic architectural elements (e.g., frameworks, roofs, and enclosures), we can achieve a finely tuned architectural structure model with hundreds of components in a short time. It is important to emphasize that without this algorithm, the modeling process of such ancient architectural structures would require manually simulating about 12 different types of arches (Figure 24), significantly increasing the complexity and time consumption for model preparation.

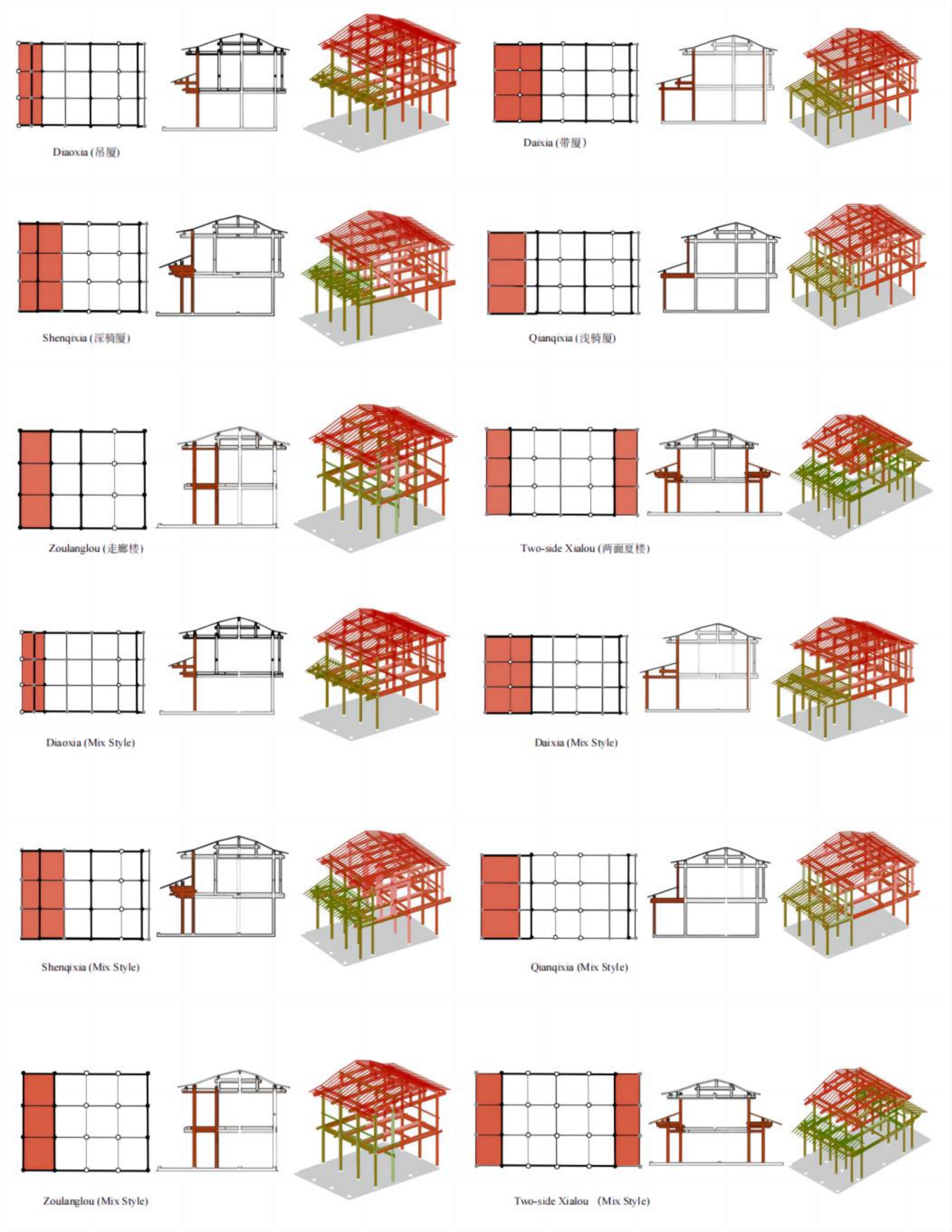


**Figure 24.** Models generated through varying topological configurations.

## 4. Future Impact and Practical Implications

This work contributes significantly to the sustainable preservation of cultural heritage. It is the interdisciplinary integration of traditional architecture and computer science. Moreover, it addresses the digital transformation issues in the traditional timber structure architecture industry. The proposed method significantly enhances its innovative value in HBIM and its practical utility in architectural design. These HBIM data are influenced not only in terms of architectural conservation and renewal but also in aesthetics and culture by the constraints between architectural components. The relationships between these components can often be automated through specific rules. For example, the use of meta-methods in mortise and tenon joints restricts different design stages as well as the spatial relationships and constraints of functions and components, and this design approach is precisely achieved through the meta-methods acting on meta-objects and meta-relationships, forming a meta-model. Utilizing this meta-model approach for the protection and renewal of complex ancient timber structures is a primary scientific contribution of this paper. Importantly, this "meta-model" method can also be applied on a broader scale to heritage buildings with highly complex features. Up until now, the parametric design in digital construction theory has mainly been applied to modern structural buildings [27]. From a theoretical standpoint, this study extends this stream of research to ancient timber structure applications by using meta-models.

HBIM is a trendy topic in the contemporary architectural industry worldwide. The advancement of techniques and their application are particularly prominent in Europe, especially in Italy. Italy, with its long history, has the leading number of UNESCO World Heritage sites, and rich cultural heritage resources. It faces complex and diverse cultural heritage preservation challenges. Thus, it has long been committed to exploring more effective and precise conservation methods. Using the topic "Historic Building Information Modelling" and the keyword "HBIM" to search the Web of Science (WoS) database, the top three contributing institutions are: Politecnico di Milano (Italy), Politecnico di Torino (Italy), and Universidad de Sevilla (Spain) (see Table 4).

**Table 4.** Main research institution results using the topic "Historic Building Information Modeling" and keyword "HBIM" in the Web of Science (WoS) database (sorted by publication contribution quantity).

| | Research Institutions | No. of Publication | HBIM Research Department |
|---|---|---|---|
| 1 | Politecnico di Milano, Italy | 78 | Department of Architecture, Built Environment, and construction Engineering (DABC) |
| 2 | Politecnico di Torino, Italy | 42 | Architecture And Design |
| 3 | Universidad de Sevilla, Spain | 38 | Escuela Técnica Superior de Arquitectura de Sevilla (ETSA) |
| 4 | Consiglio Nazionale delle Ricerche, Italy | 23 | Instituto di Scienze del Patrimonio Culturale |
| 5 | Universita Degli Studi Firenze, Italy | 20 | Dipartimento di Ingegneria Civile e Ambientale (DICEA) |
| 6 | Carleton University, Canada | 19 | Carleton Immersive Media Studio (CIMS) |
| 7 | Università Politecnica delle Marche, Italy | 19 | Dipartimento Diingegneria Civile, Edilee Architettura (DICEA) |
| 8 | Sapienza Universita di Romma, Italy | 18 | Dipartimento di Storia disegno e restauro dell'architettura (DSDRA) |
| 9 | Università degli Studi di Napoli Federico II, Italy | 18 | Dipartimento di architettura (DiARC) |
| 10 | Politecnico di Bari, Italy | 17 | Architectural and Urban Modelling Laboratory (MAULab) |
| 11 | Università di Bologna, Italy | 17 | Department of Architectureand Department of Cultural Heritage |

In China, we also witness the emerging development in HBIM research. Just five years ago, there were just a few studies applying digital information modeling to historic buildings. Today, the progress in research on this subject is remarkable. In China, the application of BIM to cultural heritage is increasingly attracting academic research. After all, it is a genuine means of technology transfer from academia to industry.

In fact, the research community, business sector, and institutional domain are all seeking an effective strategy to manage the entire lifecycle of existing buildings through specific digital tools. The time has now come for a unified, coordinated, and planned management of conservation and transformation activities. According to this approach, the focus of research lies not only in the development of BIM for heritage buildings but also on facilitating easy interchangeability between various specialized software that can be used in the conservation and design process. Furthermore, the development of customized code through "custom" scripting languages such as OWL and C# is not just an idea but has become a reality. This practical limitation of the algorithm is expected to be thoroughly resolved in the near future as it is within reach. Indeed, linking the architectural models of heritage buildings with data management and the BIM environment enables designers to effectively manage and apply complex objects within the same platform. As discussed in the previous section, using a meta-model for component management and design generation in ancient Chinese timber structures has proven its utility in HBIM and its interdisciplinary collaboration within architectural disciplines. Now, for better elucidation of results and their discussion, two key questions must be addressed.

First, why use a parametric approach with the meta-model? Firstly, the meta-model summarizes the characteristics and construction logic of architectural objects through a parametric approach. In practical applications, the meta-model can be concretized into a data-driven parametric BIM model to swiftly and automatically construct architectural information models with different characteristic component dimensions within similar timber structures. Designers can use this model to automatically perform repetitive design tasks, establish customized workflows, and handle complex timber structures.

Second, why use meta-models in HBIM? Meta-models allow technicians to create geometric figures with data set attributes based on input data (parameters). As discussed in Section 2, a meta-model can be derived by setting meta-objects, meta-properties, and meta-relationships together with specific logic and morphological relationships (meta-methods). Then, without manually inserting each part of the building, all BIM data can be added or updated in a timely manner and automatically follow geometric changes. This approach is highly efficient and coherent, thus ensuring the modeling process is much faster than traditional parametric processes while ensuring accuracy. For example, the connection points between beams and pillars—often critical intersections where structures meet via mortise and tenon, usually known as nodes—can be extracted from the entire building entity by analyzing the spatial position of the tenons and their interrelationships with surrounding components, facilitated by parametric design via meta-models. The rules for generating buildings come from various sources, including rules specific to the building's requirements (such as geometric composition relationships, functional requirements, and flow analysis) and rules adapted from other systems or algorithms (such as mimicking biological forms or microstructure of materials). Therefore, meta-models can be applied to a variety of engineering modeling, digital construction, and project analysis [39].

Figure 25 shows an integrated platform designed for HBIM, which is used for the protection and renovation of historical buildings, systematizing history and culture, and identifying better ways for Bai historical buildings to address challenges in contemporary cultural heritage conservation. From a future perspective, our strategy is to refine an "integrated" tool that provides appropriate tools to technical personnel and stakeholders for the protection and renovation of historical buildings.

**Figure 25.** HBIM Integrated Platform for Architectural Heritage Protection and Renovation.

## 5. Conclusions

To enhance the efficiency of the preservation, protection, and renovation of heritage buildings, there is need to develop more efficient, simplified, and shareable management tools. To address this issue, we propose an automated Building Information Modeling (BIM) solution for Bai wooden structures using meta-models and construction logic. It aims to achieve the reproduction and utilization of wooden structures in preservation and renovation by summarizing architectural features and their growth patterns. For this purpose, we developed a set of algorithms on the Grasshopper platform which is executed in two stages:

(1) The first stage is the generation of wooden components. This algorithm combines the advantages of traditional construction logic and computer-generated logic to sequentially generate basic component units such as columns, beams, and purlins in groups.

(2) In the second stage, the component elements generated in the last stage are classified and encoded using meta-models before adding parametric algorithms and logic based on the meta-model to enable overall parametric management of building variables such as width, depth, and floor height.

Our research shows that the parametric generation method based on meta-models has broad application prospects, capable of quickly generating three-dimensional models containing data sets and object features. With small adjustments to the input parameters, instant reconstruction of the model can be easily achieved. It is worth noticing that since a meta-model is built based on existing heritage buildings in the proposed approach, any modifications made to the three-dimensional models using the meta-model algorithm can effectively retain its cultural characteristics in the Historic Building Information Modeling (HBIM). This provides unprecedented "sustainable" opportunities for the preservation and renovation of historic buildings, while promoting efficient management of the lifecycle of heritage buildings as a whole. In addition, compared to traditional parametric design methods, this meta-model-based Historic Building Information Modeling (HBIM) software demonstrates outstanding ability in preserving the complexity and cultural significance of heritage buildings, facilitating work efficiency while making the protection of historic buildings more "sustainable".

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**Data Availability Statement:** The data that support the findings of this study are available from the corresponding author upon reasonable request.

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