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Development and Application of an Intelligent Modeling Method for Ancient Wooden Architecture

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Abstract: Building-information-modeling for cultural heritage (HBIM), which is established using surveying data, can be used to conserve architectural heritage. The development of an HBIM model for ancient wooden architecture (AWA) structures requires interdisciplinary integration. A parametric model for the main components that intelligently integrates the historical knowledge, as well as an intelligent modeling method for these components, are two critical issues required to bridge the existing gap and improve the application of HBIM. Taking an AWA structure constructed during the Liao and Song Dynasties as an example, the parametric model for the typical components, with emphasis on commonality and characteristics, were first proposed. Subsequently, an intelligent automated modeling method was developed and programmed using *Dynamo*, which can intelligently identify the component type and determine the invisible dimensions. A complicated dou-gong was successfully established with surveying data using the proposed method within five minutes, thereby validating the reliability and efficiency of this method. Furthermore, the proposed method was used to establish the HBIM model of Yingxian Wood Pagoda, which is the oldest and tallest AWA structure in China with a height of 65.88 m. The research findings will provide an essential reference for the conservation of wooden architectural heritage structures.

Keywords: HBIM; ancient wooden architecture; intelligent modeling method; Yingxian Wood Pagoda

1. Introduction

As some of the most significant immovable cultural relics in the world, ancient wooden architecture (AWA) structures are usually considered to have high social, historical and scientific value [1]. Understanding and modernized elaboration of the architectural and structural characteristics are critical for protecting such historical structures effectively [2,3]. Furthermore, the documentation of such characteristics based on three-dimensional (3D) high-fidelity modeling method is preferred. Thus, 3D digital technology has become a vital method for supporting AWA conservation [4–8]. For the protection of AWA structures, historical knowledge of the structures, including the construction regulation of assembly guidelines and component specifications, is considered essential [9,10]. First, the historical knowledge enhances the understanding of the history of an ancient structure and the knowledge of its construction method. Second, as inevitable damage and deformation will occur in

AWA structures, such knowledge is crucial for the performance evaluation and the resulting repair. A 3D digital model which can illustrate such historical knowledge and be updated frequently will be more beneficial in the sustainable protection of AWA structures.

Building information modeling (BIM) fully meets the requirements mentioned above, as it can integrate knowledge from different disciplines, such as architecture, mapping, and civil engineering. In addition, the information of a BIM model can be updated continuously [11]. Hence, BIM can be used and has been used to protect architectural heritage. Such BIM is called heritage/historic building information modeling (HBIM) [12–14]. In comparison with the traditional data collection methods (e.g., two-dimensional (2D) drawings, tables, text, and images), HBIM can express the original appearance of ancient buildings more intuitively and accurately. Similar to modern buildings, AWA buildings were also usually built with standardized components [15,16]. For example, Chinese AWA structures constructed during the Liao and Song dynasties followed "Yingzao fashi," and the corresponding components were highly standardized. Theoretically, the HBIM modeling of AWA structures can be efficiently performed using standardized components.

Various researchers have conducted valuable studies on HBIM and applied it to digitizing architectural heritage. Pocobelli et al. [17] reviewed the research findings on BIM for heritage and recommended that future studies should focus on the development of new tools that can store and share all the relevant metadata. Baik et al. [18] used Autodesk *Revit* to build a 3D model of a historic building in Jeddah (i.e., Farsi House), and the model was established based on the obtained and processed laser and images survey data. However, a components library was not proposed and introduced in the process, and the entire process was manually operated. Murphy et al. [19] identified historical details from architectural pattern books and constructed a semi-automatic parameter object library of European classical architecture using a geometric descriptive language. Quattrini et al. [20] researched irregular and complex Romanesque architecture. A 3D semantic-aware model was developed, which could connect the geometrical-historical survey data with descriptive thematic databases. The HBIM model of the Church of Santa Maria at Portonovo was established using this method. For the application of HBIM in AWA, Park [21] defined a parametric relationship between the structural elements in Hanok and developed a systematic data library for such elements.

Despite the efforts mentioned above, it is still required that HBIM should be further developed for modeling AWA structures in the following three aspects:

(1) Standardized component libraries for typical components of AWA buildings with an emphasis on historical knowledge, especially commonality and characteristics. The authors have proposed multi-level details of BIM models for different components of AWA buildings, which focused on various requirements at different protection phases [22]. However, the authors found out that different components with different knowledge exhibited identical appearance (which is illustrated in detail in Section 2), thus extremely hindering professionals in surveying and civil engineering from understanding the actual information about different components. This feature is quite different from masonry and stone heritage buildings [23], and currently, is not well considered. A parametric model of typical components with emphasis on commonality and characteristics which intelligently integrates the historical knowledge and can be easily used by conservation workers will be beneficial for dealing with the diversity of practitioners protecting AWA buildings [24–26].

(2) Obtaining invisible dimensions due to complicated stacking. Different from modern architecture and other types of historical buildings, the construction of AWA structures is complex [27]. For example, there are more than 480 dou-gongs in Yingxian Wood Pagoda, with 54 types. Each dou-gong is stacked with more than 20 components [28]. A highly manual deduction based on historical knowledge is usually applied to calculate the invisible dimension. Although the deduction algorithm may be simple, it is rather time-consuming because experts with specific knowledge are needed, and thousands of components are required for identification and deduction. An intelligent algorithm and a corresponding program, which can integrate the knowledge, should be developed to automatically identify the type of component and deduce the invisible dimensions.

(3) The method for automatically modeling most components. The current trend in practice is the use of advanced automation technology [6,7,15,18,29]. However, the automatic modeling of an entire AWA structure or even a single dou-gong remains a significant challenge. An automatic modeling method for most components is more applicable and convenient to check [30]. If standardized component libraries are established, the corresponding parametric models require two types of input parameters (i.e., visible dimensions, which can be obtained using a surveying method and deduced invisible dimensions, which can be calculated automatically and intelligently). The model of such a component can be established theoretically. However, due to the two issues highlighted above, a systematic method that incorporates intelligent identification of the type of components, deduction of invisible dimensions, and automatic modeling, is rarely reported.

In addressing these issues using the Chinese AWA structures constructed during the Liao and Song dynasties as an example, the knowledge of typical components, with an emphasis on commonality and characteristics, was further identified. The corresponding parametric models for the typical components, with an emphasis on commonality and characteristics, were recommended. Subsequently, an intelligent automated modeling method was developed using *Dynamo* with three critical functions, which were the intelligent identification of the type of components, deduction of invisible dimensions, and automatic modeling of the structures. A complicated dou-gong was established with surveying data using this method to validate the reliability of the proposed method. Furthermore, the method was applied to establish the HBIM model of the Yingxian Wood Pagoda, which is the oldest and tallest ancient wooden architecture in China with a height of 65.88 m. The research findings will provide an essential reference for the conservation of wooden architectural heritage structures.

2. Parametric Model for Typical Components with Emphasis on Commonality and Characteristics

The dou-gong is the most important and sophisticated element in Chinese AWA structures. The dou-gong is composed of four typical components (i.e., dou, gong, ang, and fang) and is assembled by following specific principles (as shown in Figure 1a). Similar to modern architecture, the Chinese AWA also adopts the fundamental concepts of standardization and modularization. In the AWA structures constructed during the Liao and Song dynasties, the typical components were highly standardized. The "caifen zhi" in "Yingzao fashi" specified the shape and modulus of each component [31]. Specifically, the absolute value of a specific characteristic size, as well as the proportional relationships between other characteristic sizes and this specific characteristic size, were prescribed. Therefore, parametric models for such components can be developed.

It should be noted that these standard key components exhibit commonalities and characteristics. Taking the gong for instance (Huagong, Linggong, Guazigong, Mangong and Nidaogong as shown in Figure 1a,b), the gong in different positions of a dou-gong has a particular name due to different proportional relationships, although an identical appearance is observed for different gongs through a parametric modeling view. The identical appearance is the commonality between different gongs, while the various names and proportional relationships can be considered as characteristics, which is essential historical knowledge.

During the digital protection of such AWA structures using BIM, a unified parametric model reflecting commonality, rather than several personalized models reflecting characteristics, is preferred by surveyors and civil engineers [32–36]. However, some parameters (i.e., sizes) are invisible and unmeasurable because typical components in a real dou-gong are stacked. The historical knowledge of characteristics, which is not precisely known, should be introduced to determine the type of element and to deduce such sizes.

Consequently, the development of a unified parametric model with intelligent reasoning is required. Specifically, a unified model reflecting commonality is used, and the characteristics are internally integrated for deduction. The commonality and characteristics of such a model should be analyzed comprehensively. Then, the unified parametric model can be proposed, and the characteristics should be mathematically expressed and integrated. Taking "gong" in the ancient wooden heritage of

the Liao and Song dynasties as an example, the fundamental idea of the corresponding parametric model, which integrates the commonality and characteristics, is introduced.
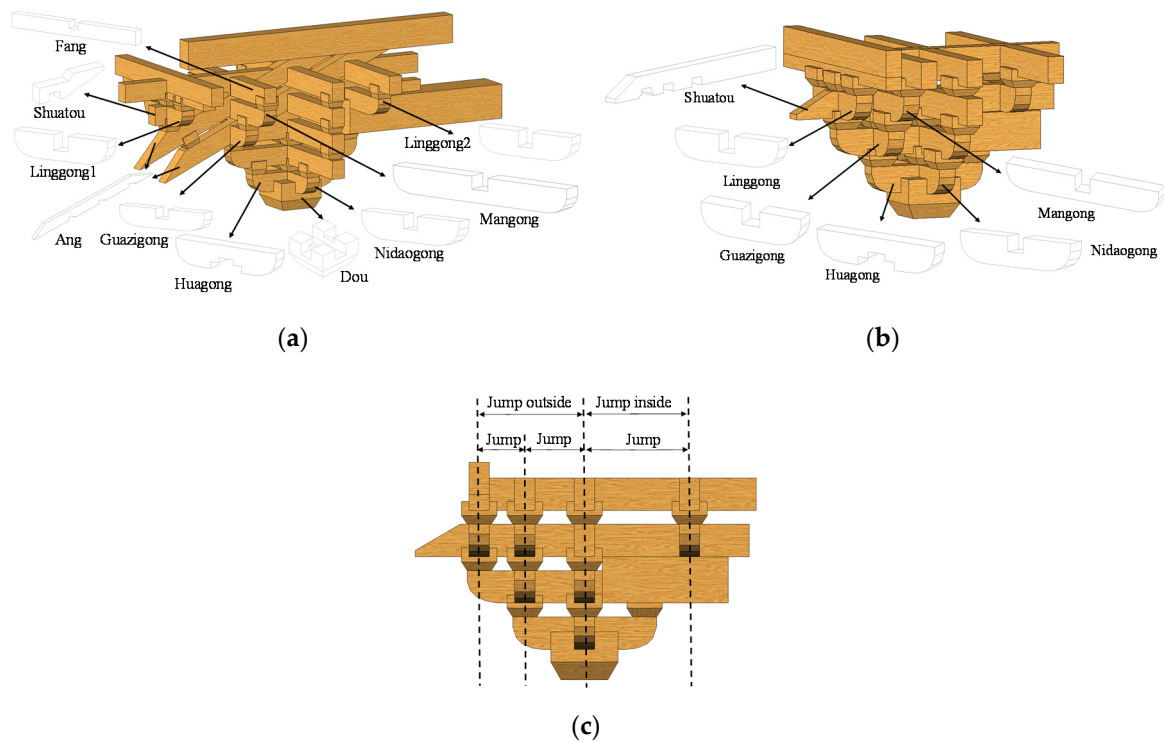
Figure 1. (**a**) Dou-gong with ang; (**b**) dou-gong without ang; (**c**) jump in dou-gong.

2.1. Characteristics of Gong

The gong is a typical component in dou-gong that is located in the notch of "dou" (such as the "Huagong," "Nidaogong," "Guazigong," "Mangong," and "Linggong1," as shown in Figure 1a) or on the "jump" (such as the "Linggong2," as shown in Figure 1a). The gong usually has an upward-bowed shape and transfers the vertical and horizontal loads. According to its position in dou-gong and the historical knowledge, the gong can be categorized into five types, which are "Huagong," "Nidaogong," "Guazigong," "Mangong," and "Linggong," as shown in Figure 1a,b. From the perspective of the gong shape, two notable characteristics are observed, including a notch carved in the middle of the gong and "juansha" at both ends. For the notch, the gong is used to connect the upper and lower components through intersection. The notch is a flat notch carved at the top or bottom of the gong. Remarkably, only Huagong carves the notch at the bottom, whereas the other four types of gongs carve at the top.

As for the juansha, it is an aesthetic border. To manufacture a "juansha," the end of the gong is first divided into the same number of parts (noted as a variable m) along the height and length directions, as shown in Figure 2. The length and height of "juansha" are denoted as b_1 and h_1, respectively, as shown in Figure 2. After that, m points are assigned and numbered along the length and height directions. Specifically, the nodes along the length direction are numbered from m (the red point shown in Figure 2) to 1, whereas the nodes along the height direction are numbered from 1 (the blue point shown in Figure 2) to m. The ith point in the height direction and the ith point in the length direction are connected using a straight line. The m-minus-one points of intersection (the black points shown in Figure 2) can be obtained from the two adjacent straight lines. In combination with the two endpoints of "juansha" (i.e., point m in the length direction and point 1 in the height direction), the outline of "juansha" is determined and presented in multiple linear segments.
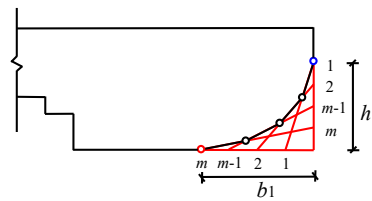
Figure 2. Schematic diagram of juansha.

2.2. Parametric Model for Gong

From the above discussion, it can be observed that Huagong is significantly different from other types of gongs. Therefore, a unique model is required for Huagong. In contrast, Nidaogong, Guazigong, Mangong and Linggong exhibit significant common characteristics. Specifically, these four types of gongs all have an upward notch at the middle of the gong, and a common model can be developed for these gongs. Hence, two types of common models are required for these five types of gongs.

Before the introduction of these models, the fundamental principle of "caifen zhi" [31] is briefly introduced. "Cai" refers to a wood member with a height-width ratio of 3:2, and it is categorized into eight grades in Yingzao fashi. Each grade has different absolute sizes, but "cai" is divided into proportional sections in both the height and width directions; the total height and width are divided into 15 and 10 "fen," respectively. The other dimensions, such as the total length and the dimensions of notch, are also expressed in "fen." By taking Huagong as an example using the first grade of cai, Huagong is designed such that it has a total height and width of 278.1 and 185.4 mm, respectively. A "fen" in this case is equal to 18.54 mm. The total length of such a component is 72 "fen," i.e., 1334.88 mm. Using the second grade of cai for the Huagong, it has a total height of 255 mm and a width of 170 mm, and a "fen" in this context is equal to 17 mm. The total length of such a component is also 72 "fen," but with a value of 1224 mm. Non-professionals may not easily understand the traditional description, and therefore, a modern description method for Yingzao fashi is required.

A parametric model for Huagong, as shown in Figure 3a, was developed with 10 parameters as follows: total height h, height of "juansha" h_1, first height of notch h_2, second height of notch h_3, total length b, length of "juansha" b_1, first length of notch b_2, second length of notch b_3, width t, and number of parts of "juansha" m. As mentioned earlier, the historical knowledge should be introduced to deduce the invisible and unmeasurable parameters. The proportional relationships of each parameter specified in "caifen zhi" are elaborated, and the original description can be transformed as follows: (1) the length of Huagong is 72 fen; (2) juansha is divided into four parts (i.e., $m = 4$); (3) the length and height of juansha are 16 and 9 fen, respectively; (4) a notch is carved at the bottom with a total height of 5 fen and a total length 20 fen; (5) the first height and length of the notch are 1 and 10 fen, respectively. The total height and width in the parametric model of Huagong are 15 and 10 fen, respectively. If the grade of the cai is given, the absolute value of the total height and width can be determined. The characteristic parameters in the parametric model of Huagong can be calculated using Equation (1).

In comparison with Huagong, a flat notch in the middle of the top is adopted for the other four types of gongs. A unified parametric model is developed, as shown in Figure 3b. This model is designed with eight parameters as follows: total height h, height of "juansha" h_1, height of notch h_2, total length b, length of "juansha" b_1, length of notch b_2, width t, and number of parts of "juansha" m. The proportional relationships of each parameter are also introduced for these four types of gongs as the characteristics. Due to length limitations, the original description of the proportional relationships specified in Yingzao fashi is not converted here, but the proportional relationships are directly presented in Table 1.

$$(b, b_1, b_2, b_3, h_1, h_2, h_3, t) = (72/15, 16/15, 2/3, 4/3, 3/5, 1/15, 1/3, 2/3)h,$$
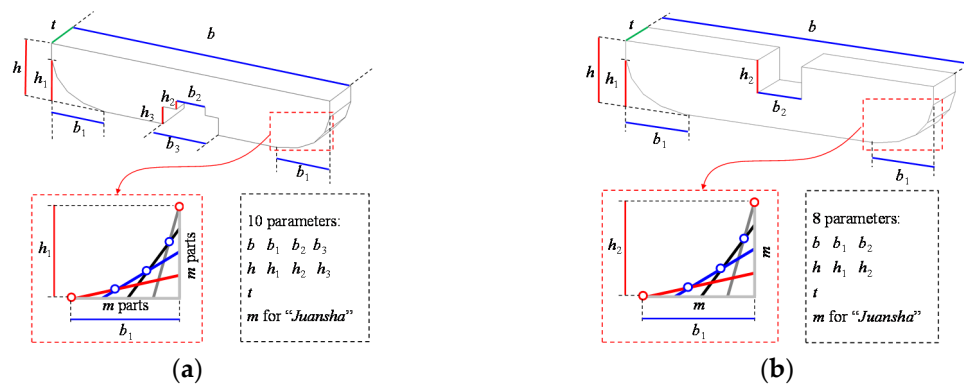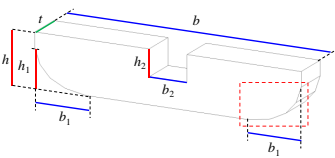$$m = 4 \tag{1}$$

Figure 3. (**a**) The common parametric model of Huagong; (**b**) the common parametric model of other types of gongs.

Table 1. The relations of characteristic parameters in parametric models of the other four types of gongs.

Parametric Model.		The Proportional Relationships of Each Parameters
	Nidaogong	$(b, b_1, b_2, h_1, h_2, t)$ = (62/15, 14/15, 8/15, 3/5, 2/3, 2/3)h; $m = 4$
	Guazigong	$(b, b_1, b_2, h_1, h_2, t)$ = (62/15, 16/15, 8/15, 3/5, 2/3, 2/3)h; $m = 4$
	Linggong	$(b, b_1, b_2, h_1, h_2, t)$ = (72/15, 4/3, 8/15, 3/5, 2/3, 2/3)h; $m = 5$
	Mangong	$(b, b_1, b_2, h_1, h_2, t)$ = (92/15, 4/5, 8/15, 3/5, 2/3, 2/3)h; $m = 4$

Based on the above discussion, a parametric model system with an emphasis on commonality and characteristics is proposed, as shown in Figure 4 for the gongs. The common parametric models stated above are illustrated on the left side, which generalize components with an identical appearance and express them from a mathematical point of view. If all the parameters can be obtained through surveying and mapping technologies, the model can then be established directly. However, the parameters cannot be usually obtained owing to stacking. The historical knowledge of Chinese AWA structures is usually introduced to deduce the invisible parameters, and the proportional relationships are integrated, as shown on the right side of Figure 4. The fundamental idea of the reasoning method is that the component type is identified first through the proportional relationships between the visible dimensions; the invisible dimensions of the component are deduced based on visible dimensions and proportional relationships between the visible and invisible dimensions.

2.3. Parametric Model of the other Components

The dou, as shown in Figure 5, is a square wooden block with a cross-mortise notch, which supports the weight of the components resting on it. The fang, as shown in Figure 6, is a horizontal or vertical inserting component with a relatively simple configuration. It is a cuboid with a flat notch in the middle of the top, and the notch is used to connect with other components. Due to the length limitation, the parametric models for the dou with an emphasis on commonality and characteristics are directly presented in Figure 5, and the corresponding parameters and construction guidelines specified in Yingzao fashi are also determined and introduced, similar to those of the gongs. For the fang, only one type exists; a commonly parametric model is also directly given and presented in Figure 6.
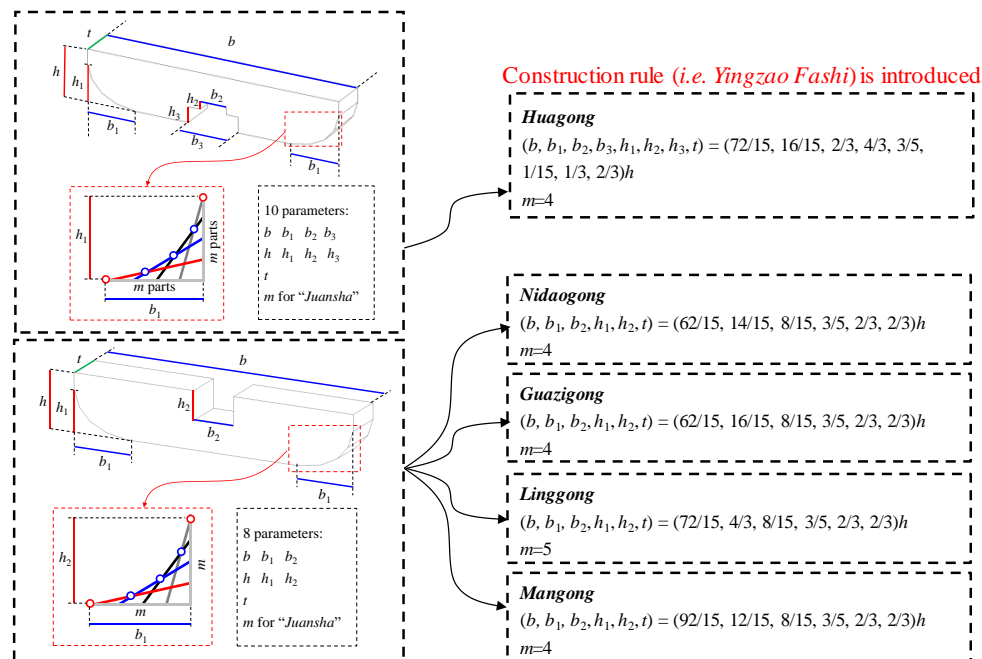
Construction rule (*i.e. Yingzao Fashi*) is introduced

Huagong
$(b, b_1, b_2, b_3, h_1, h_2, h_3, t) = (72/15, 16/15, 2/3, 4/3, 3/5, 1/15, 1/3, 2/3)h$
$m=4$

Nidaogong
$(b, b_1, b_2, h_1, h_2, t) = (62/15, 14/15, 8/15, 3/5, 2/3, 2/3)h$
$m=4$

Guazigong
$(b, b_1, b_2, h_1, h_2, t) = (62/15, 16/15, 8/15, 3/5, 2/3, 2/3)h$
$m=4$

Linggong
$(b, b_1, b_2, h_1, h_2, t) = (72/15, 4/3, 8/15, 3/5, 2/3, 2/3)h$
$m=5$

Mangong
$(b, b_1, b_2, h_1, h_2, t) = (92/15, 12/15, 8/15, 3/5, 2/3, 2/3)h$
$m=4$

10 parameters:
b b_1 b_2 b_3
h h_1 h_2 h_3
t
m for "*Juansha*"

8 parameters:
b b_1 b_2
h h_1 h_2
t
m for "*Juansha*"

Figure 4. Parametric model summary of the gongs.

Construction rule (*i.e. Yingzao Fashi*) is introduced

Ludou
$(b, b_1, b_2, h, h_1, h_2, h_3, t, t_1, t_2) = (32/15, 8/5, 2/3, 4/3, 8/15, 8/15, 4/15, 32/15, 2/3, 8/15)H$
H for "*Cai*"

Jiaohudou
$(b, b_1, b_2, h, h_1, h_2, h_3, t, t_1, t_2) = (6/5, 14/15, 2/3, 2/3, 4/15, 4/15, 2/15, 16/15, 2/3, 1/10)H$
H for "*Cai*"

Qixindou （*under the Shengtoumu*）
$(b, b_1, b_2, h, h_1, h_2, t, t_1) = (16/15, 4/5, 2/3, 2/3, 4/15, 4/15, 16/15, 2/3)H$
H for "*Cai*"

Qindou （*above the center of Gong*）
$(b, b_1, b_2, h, h_1, h_2, t) = (16/15, 4/5, 2/3, 2/3 , 4/15, 4/15, 16/15)H$
H for "*Cai*"

Sandou
$(b, b_1, b_2, h, h_1, h_2) = (16/15, 4/5, 2/3, 2/3 , 4/15, 4/15, 14/15)H$
H for "*Cai*"

Pingpandou
$(b, b_1, h, h_1, t) = (16/15, 4/5, 2/5, 4/15, 16/15)H$
H for "*Cai*"

11 parameters:
b b_1 b_2
h h_1 h_2 h_3
t t_1 t_2
H for "*Cai*"

$h_3=0, t_2=t/2$
8 parameters

$h_3=t_1=0, t_2=t/2$
8parameters

$b_2=h_2=h_3=t_1=0, t_2=t/2$
6 parameters

Figure 5. Parametric model summary of dou.

Construction rule (*i.e. Yingzao Fashi*) is introduced

Fang
$(b_1, h_1, t) = (8/15, 2/3, 2/3)h$
b

5 parameters:
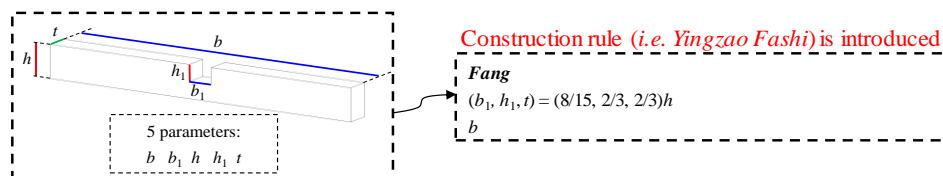b b_1 h h_1 t

Figure 6. Parametric model of the fang.

The ang is located on the central line of the front and back of the dou-gong, and it stretches longitudinally to the front and back of the dou-gong to connect with the inside and outside of the

jump, which is schematically illustrated in Figure 1a. Shuatou is a component that locates the top of the ang or Huagong and is perpendicular to Linggong, as depicted in Figure 1a,b. Commonality is rarely observed for the ang and shuatou, and they are rarely used. Therefore, the parametric model was not considered here, and the model for the ang and shuatou was separately established using the traditional method.

3. Intelligent Automated Modeling Method Developed Using *Dynamo*

In actual engineering practice, the dou-gong is stacked, and only some exposed dimensions can be obtained for each component. In developing an intelligent automated modeling method, three issues should be carefully addressed: (1) the type of component should be first determined based on only the appearance (e.g., Nidaogong or Linggong) and the exposed dimensions; (2) then, the invisible dimensions can be automatically deduced according to the component type and exposed dimensions, in which the characteristics (i.e., proportional relationships between the exposed and invisible dimensions) associated with the type of component should be introduced; (3) after all the dimensions of each component are obtained, it is preferred that the model is established automatically.

The traditional "family" in *Revit* can be used to construct the common model, but all parameters should be manually inputted to establish the model [37,38]. Furthermore, the existing knowledge cannot be integrated to deduce the invisible dimensions, hindering the intelligent modeling. *Dynamo*, a built-in visual programming tool in *Revit*, can be used to solve these two problems effectively. This solution is attributed to the fact that it is easy to achieve the integration of logical judgment (i.e., the identification of component type) and operation (i.e., the calculation of invisible dimensions based on the exposed dimensions) through programming, leading to intelligent reasoning [39–42]. In addition, using *Dynamo* supports automated modeling based on parameters [43,44]. *Dynamo* in *Revit* 2017 was adopted in this study, and the intelligent automated modeling method was developed using the following typical nodes, including the *Point.ByCoordinates*, *Line.ByStartPointEndPoint*, *PolyCurve.ByPoints*, *Surface.ByPatch*, and *Solid.ByJoinedSurfaces*. By taking "gong" as an example, the method was introduced in developing the parametric model for these components.

3.1. Identification Method for the Component Type

As indicated in Figure 1a, there are significant differences between the appearances of the dou, gong, ang, and fang, resulting in the convenient identification of these components through visual recognition. However, the specific types of components with similar appearances, such as Nidaogong or Linggong, requires further identification of peculiar characteristics. Two issues should be considered for such identification, which are the variables for identification and the corresponding accepted relative error.

For evaluating the variables, there are different ratios (i.e., proportional relationships) between specific parameters or a particular value for m. Such ratios and particular values can be regarded as variables and used for identifying the type of the component. For Nidaogong, Linggong, Mangong, and Guazigong, using a common model, seven parameters (i.e., h, h_1, b, b_1, b_2, t, and m) in such a model are the exposed and measurable parameters; only h_2 requires deduction. b/h, b_1/h, and m can be adopted as three variables, resulting in a vector. The expressions, (62/15, 14/15, 4), (62/15, 16/15, 4), (72/15, 4/3, 5), and (92/15, 12/15, 4) are used to identify Nidaogong, Guazigong, Linggong, and Mangong, respectively. Three steps are considered as follows (as shown in Figure 7): (1) m is first used for identifying Linggong because only this type of gong is designed with m equal to 5. (2) The ratio of b/h is used for identifying Mangong because the value of b/h for Nidaogong and Guazigong is 62/15, which is significantly different from that of Mangong (92/15). (3) The ratio of b_1/h is adopted to distinguish Nidaogong from Guazigong.
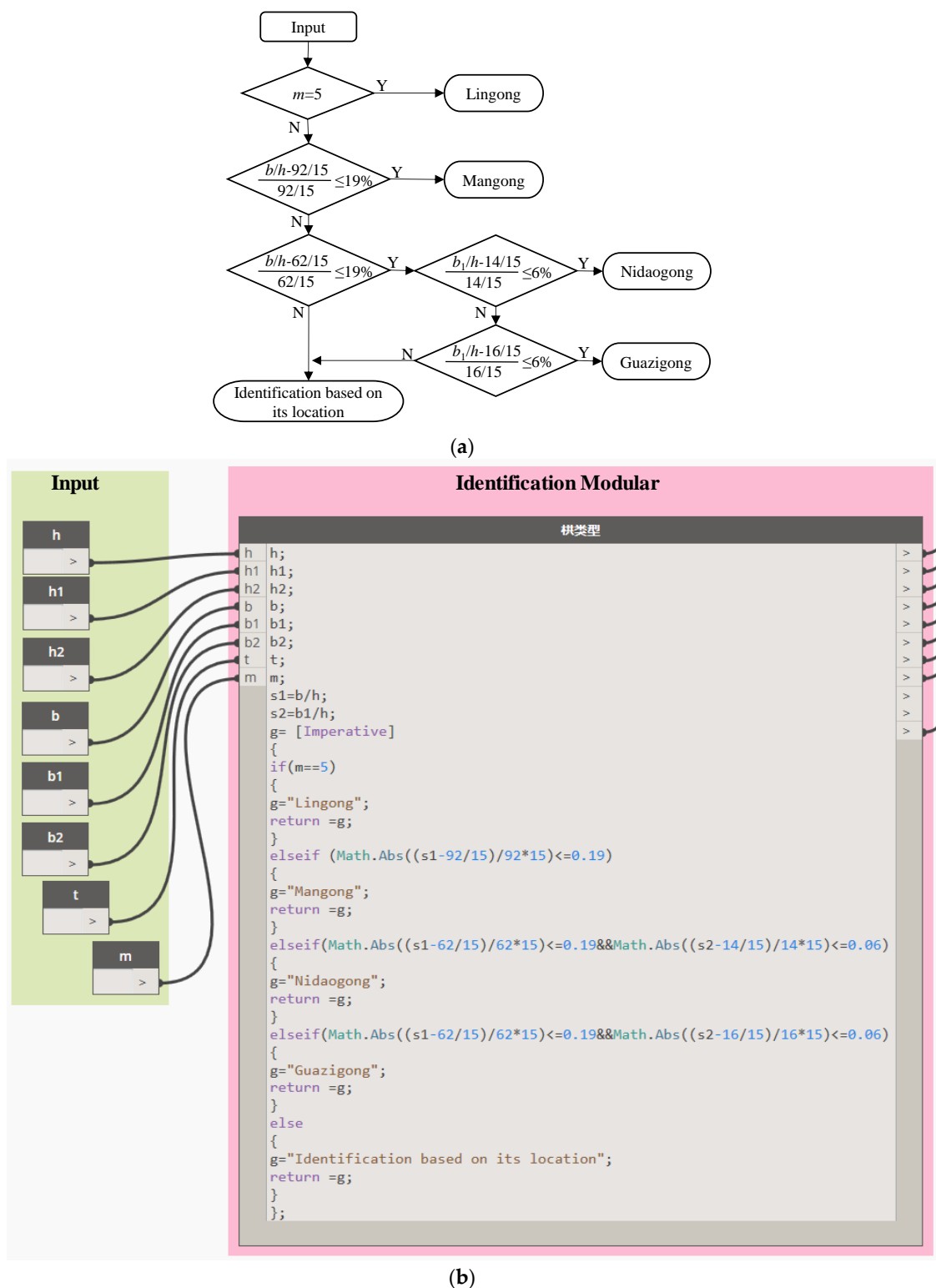
(a)

(b)

Figure 7. Identification method for the type of gong: (**a**) logical diagram; (**b**) implementation diagram.

For the accepted relative error of variables, the error between the expected and measured values of the ratios given above exists because manufacturing precision was relatively low during the Liao and Song dynasties. Hence, some thresholds of the relative error need to be introduced to assist in the identification of the component type. The threshold for the error in b/h is adopted as 19%, through which the acceptable values of b/h for Manggong and Nidaogong (as well as Guazigong) range from

4.97–7.3 and 3.35–4.92, respectively, leading to the identification of these components. The threshold for the error in b_1/h is taken as 6%, through which the acceptable values of b_1/h for Nidaogong and Guazigong range from 0.88–0.99 and 1–1.13, respectively, also resulting in the identification of these two components.

The identification method described above is programmed in *Dynamo*. The corresponding logic diagram and implementation diagram in *Dynamo* are presented in Figure 7. Detailed procedures are given as follows. (1) All the available parameters should be input first. (2) b/h and b_1/h are calculated, and the type of gong is defined as a variable named g. (3) If m is equal to 5, Linggong is assigned to g; otherwise, the absolute relative error between b/h and 92/15 is calculated. If the absolute relative error is not higher than 19%, the type of gong is identified as a Mangong. Otherwise, the absolute relative error between b/h and 62/15 is calculated and is mostly not greater than 19%. Then, the absolute relative error between b_1/h and 14/15 is further calculated, and if this error is not higher than 6%, the component is identified as Nidaogong. Otherwise, the absolute relative error between b_1/h and 16/15 is calculated, and if it does not exceed 6%, the gong is then identified as Guazigong. (4) If the gong does not belong to any of the situations mentioned above, "identification based on its location" is assigned to g. (5) Finally, the result is transferred to the "parameters reasoning program.".

3.2. Intelligent Reasoning Method for the Invisible Dimensions

In actual engineering practice, the dou-gong is usually stacked. The exposed and measurable dimensions (i.e., the input parameters presented in Section 3.1) in the common model can be obtained, whereas the invisible dimensions are the parameters that should be reasoned in this model. During this procedure, the historical knowledge (i.e., the proportional relationships between each parameter) is required and integrated in *Dynamo* as the characteristics.

Through the identification method of the type of component, the component type is transferred to the program using a variable g. The proportional relationships between the exposed and invisible dimensions are integrated as several functions. Such functions are selected according to "g" (i.e., the identified type) and called to reason the invisible dimensions. h_2 is the invisible dimension of the gong that is to be deduced. If Linggong is identified, six functions integrated in *Dynamo*, which specify the relationships between the exposed dimensions (i.e., h, h_1, b, b_1, b_2, and t) and the invisible dimension (i.e., h_2), are used for calculating h_2. Then, excluding the maximum and minimum values of the calculated h_2, the average value of the other four h_2 is calculated and regarded as the acceptable value. The intelligent reasoning method for the invisible dimensions is shown in Figure 8. It should be noted that currently, there is no universal agreement on the reasoning method. Thus, a simple engineering method is adopted in this study to illustrate the fundamental principle of the intelligent reasoning method. In future studies, the framework described in this study can still be used, while a new algorithm can be introduced to improve the accuracy or expanded to AWA structures built during other dynasties (e.g., Qing dynasty) with different historical knowledge.

3.3. Automated Modeling Method

All the parameters, including the exposed and deduced parameters, were obtained to establish the model. An automated modeling method was subsequently required. The traditional modeling method in *Revit*, i.e., points-to-lines, lines-to-surfaces, and surfaces-to-solid, as shown in Figure 9, was also programmed based on *Dynamo*.

The outline of each component in the dou-gong can be considered as a polyline, and some characteristic points (as shown in Figure 10a) are defined. In *Dynamo*, such points can be represented using coordinate points, and the coordinate values of each point can be determined by the characteristic parameters in the common model. Before the characteristic points are created, such points should be numbered, which will facilitate the resulting definition of the relationships between such points (i.e., the generation of lines). Nidaogong, Mangong, Guazigong, and Linggong are also adopted here as an example to illustrate the method. The characteristic points of the gong are presented in Figure 10a,

and the coordinate values can be determined based on the parameters in the common model. For example, the coordinates of No. 1–5 in Figure 10a are given as follows: 1 $(0, 0, h_1)$, 2 $(0, 0, h)$, 3 $(0, t, h)$, 4 $(0, t, h_1)$, and 5 $((b-b_2)/2, t, h)$.
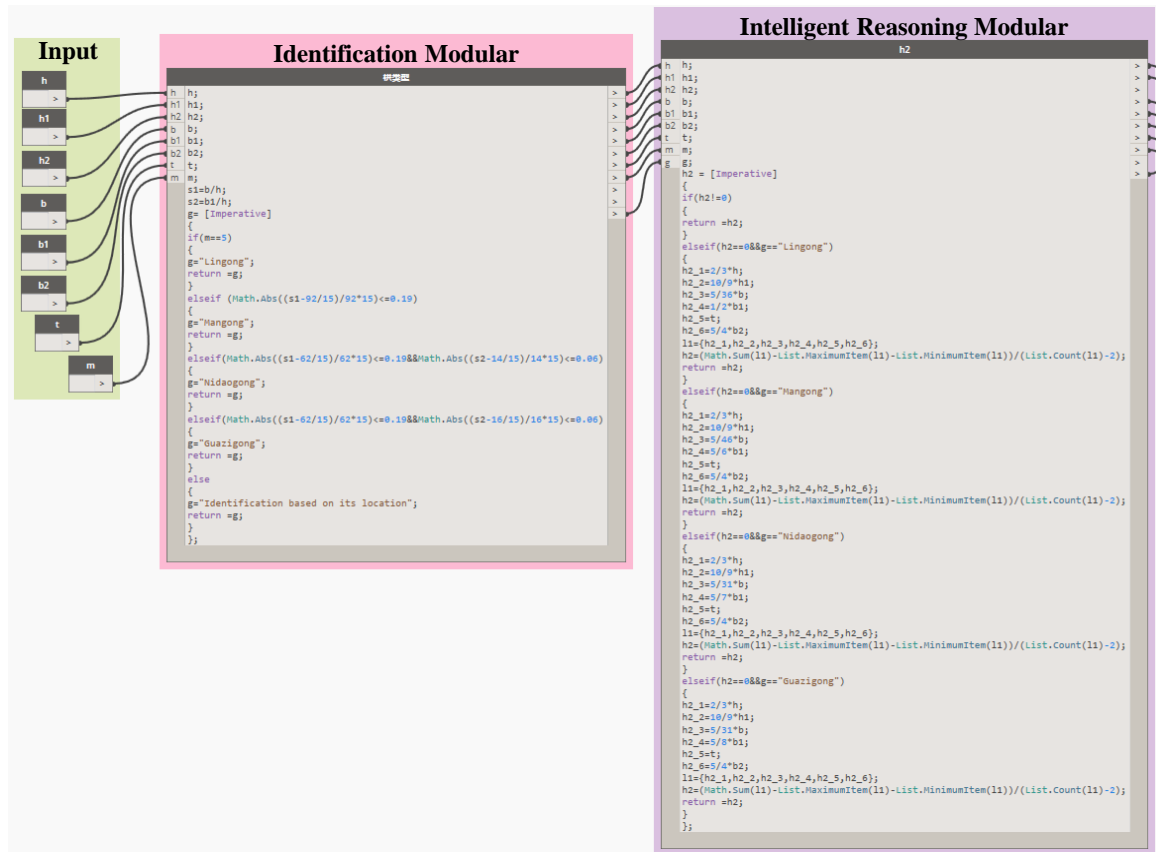

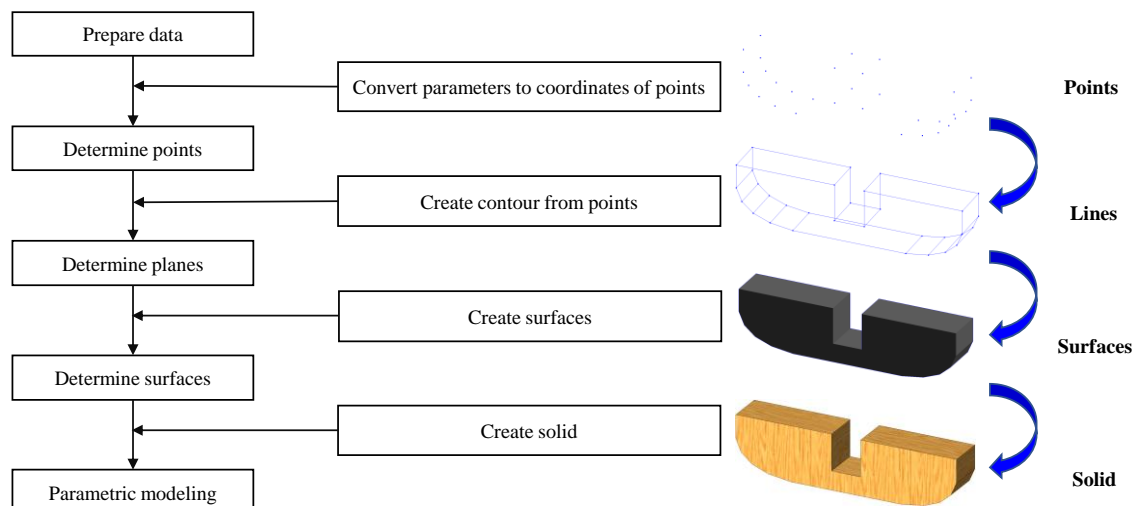**Figure 8.** The intelligent reasoning method for the invisible dimensions in *Revit Dynamo*.

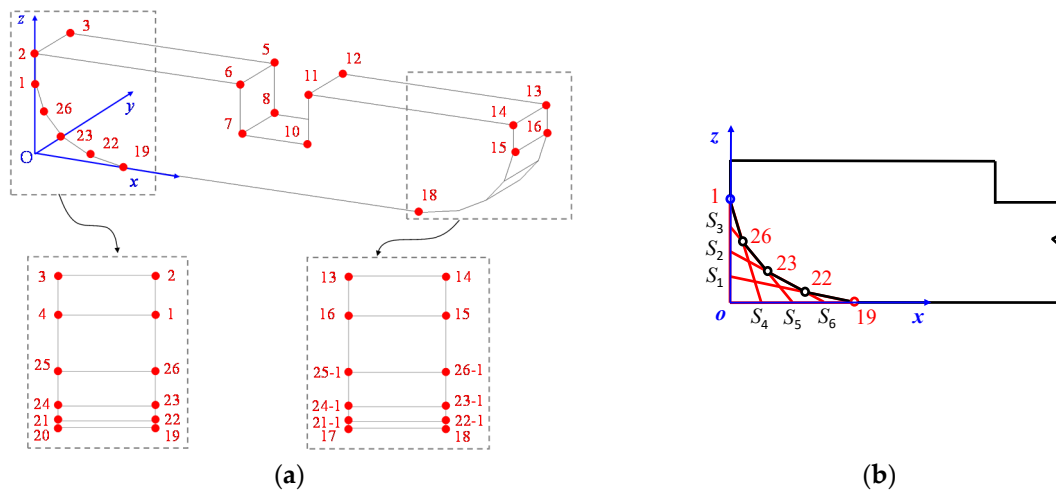**Figure 9.** The fundamental concept of the automated modeling method.

Figure 10. Characteristic points in gongs: (**a**) point numbering; (**b**) creation of the points of juansha.

(1) Creating points

For the gong, two types of characteristic points were considered and defined, which were the points on juansha (e.g., 22, 23, and 26 in Figure 10b) and the other points (e.g., 1, 2, and 3 in Figure 10a). For the other points, with all the parameters for the common model, the coordinates of such points can be obtained by simple addition and subtraction. Subsequently, *Point.ByCoordinates* in *Dynamo* was directly used to create the points. For the points on juansha, taking *m* equal to 4 as an example, the process of creating such points involved the following four steps: (1) h_1 (the distance between Point 1 and Point O in Figure 10b) and b_1 (the distance between Point 19 and Point O in Figure 10b) were equally divided into four parts. *Point.ByCoordinates* in *Dynamo* was also used to create the points obtained through such equalization (i.e., S_1, S_2, S_3, S_4, S_5, and S_6 in Figure 10b). (2) *Line.ByStartPointEndPoint* was called to connect Points 1 and S_4, Points S_3 and S_5, Points S_2 and S_6, and Points S_1 and 19, and four lines were generated. (3) The four generated lines were named L_1, L_2, L_3, and L_4, respectively, and the intersections of L_1 and L_2, L_2 and L_3, and L_3 and L_4 were points on juansha that were required for the modeling. *Geometry.intersect* was subsequently used to determine the intersections (i.e., Points 22, 23, and 26) of 4 lines. Meanwhile, the corresponding coordinates were also obtained through *Point.X*, *Point.Y*, and *Point.Z*. (4) Most components were symmetrical, through which the characteristic points of the other three parts of juansha can be determined using the function, *Translate*, in *Dynamo*. For example, according to the symmetry in the direction of length *b*, Point 26-1 can be determined from Point 26. Based on the symmetry in the direction of thickness *t*, Point 25 can be determined from Point 26, and Point 25-1 can be determined from Point 26-1.

(2) Creating lines, surfaces, and solid

After creating the points, the contour of the component was first established. The points on each surface were organized to facilitate the creation of surfaces, and the connection relationships between these points were defined in a single list. The lists for all the surfaces were stored in *List.Join* in *Dynamo*. Then, *PolyCurve.ByPoints* in *Dynamo* was used to connect the points in the lists, and several closed curves can be generated automatically, leading to the contour of each surface and the component. Subsequently, *Surface.ByPatch* in *Dynamo*, which could be used to create a surface based on several closed curves through filling, was used to create all the surfaces. A surface list was defined there to organize all the surfaces attributed to the component. Finally, *Solid.ByJoinedSurfaces* in *Dynamo*, which can create a solid based on all surfaces, was called to build the solid.

The procedure described above was programmed in *Dynamo*. An example of the intelligent automated modeling of Nidaogong, Mangong, Linggong, and Guazigong is presented in Figure 11, which all share a common model.
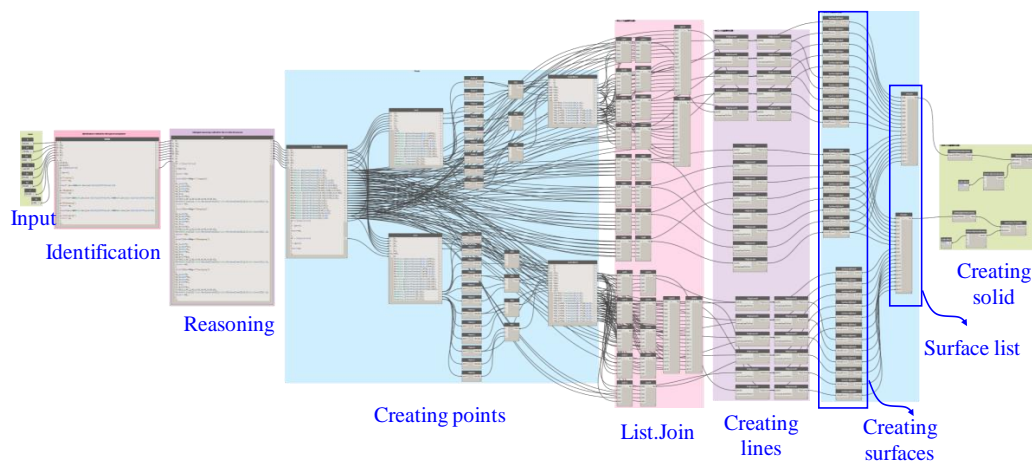
Figure 11. Automatic construction of the parametric model of gongs in *Revit Dynamo*.

4. Verification and Application

4.1. Verification of the Proposed Method

The HBIM model of a dou-gong in Yingxian Wood Pagoda was established using the proposed intelligent modeling method to verify the feasibility of the proposed method. A dou-gong located at the outer groove of the second hidden layer of this pagoda was selected because it contains four kinds of dou, five types of gong, two types of fang, and one shuatou, which includes almost all the types of dou-gong components in this pagoda. The mapping data, which was obtained by Guixiang Wang of the Beijing University of Civil Engineering and Architecture in 1991, was used as the input data. It is worth mentioning that although this data was obtained in 1991 using manual mapping tools and total station instruments, it is still the most comprehensive data of Yingxian Wood Pagoda. A complete set of drawings was drawn and reserved by the Beijing University of Civil Engineering and Architecture. These drawings contain the surveying and mapping work of the entire structure of Yingxian Wood Pagoda as well as all single dou-gongs (Figure 12a).
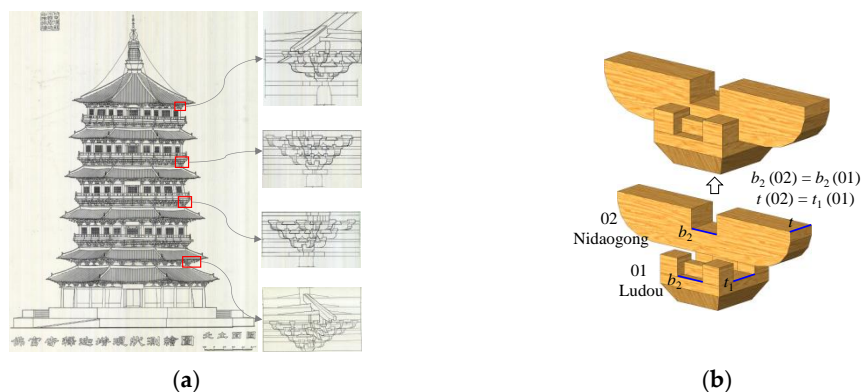

(**a**)   (**b**)

Figure 12. Drawings and transfer relationships: (**a**) drawings obtained by Guixiang Wang; (**b**) the transfer relationships between the shared parameters of adjacent components.

The actual object diagram photographed by the authors and three views drawn by Guixiang Wang are compared in Figure 13a. Three critical issues for the intelligent modeling of the HBIM model are summarized as follows. (1) The measured dimensions of the visible parts were directly obtained from the three views of each component. (2) The components in dou-gong were determined and established sequentially from the bottom layer to the top layer; (3) it was assumed that there was no

gap between the tenon-and-mortise connection, which indicates that the related parameters of two adjacent connecting components were identical (Figure 12b).

Actual picture(taken by the author) The mapping data 3D modeling

(**a**)

18

	h	b	b₁	b₂	b₃	b₄	t	h₁	h₂	h₃	h₄	b₅	b₆	b₇	b₈	Type
18	260	/	345	190	150	330	160	86.7	86.7	86.7	86.7	160	160	160	160	Shengtoumu

	h	b	b₁	t	Type	h₁
15 16 17	260	/	160	150	Pubanfang Pubanfang Zhutoufang	173.3

	h	b	b₁	t	Type	h₁
14	260	/	160	150	Pubanfang	173.3

	h	h₁	h₂	b	b₁	b₂	t	t₁	Type
13	190	80	80	285	210	160	300	160	Qixindou

	h	h₁	b	b₁	b₆	b₇	b₈	t	h₂	h₃	h₄	h₅	b₂	b₃	b₄	b₅	Type
12	255	160	/	235	370	155	335	160	35.4	62.9	49.7	85	160	243.9	160	160	Shuatou

	h	b₁	t	Type	h₁	
	255	160	150	Zhutoufang	170	11

	h	h₁	b	b₁	b₂	t	Type	h₂
09	255	150	1010	250	160	150	Lingong	156.7

	h	h₁	b	b₁	b₂	t	Type	h₂	
	255	150	1760	210	160	160	Mangong	169.9	10

	h	h₁	b	b₁	b₅	b₆	t	h₂	h₃	h₃	h₄	b₂	b₄	Type
08	250	140	/	185	310	335	160	35.4	243.9	46.4	82.5	150	160	Huagong-2

	h	h₁	b	b₁	b₂	t	Type	h₂	
	250	160	1760	220	160	160	Mangong	167.5	07

	h	h₁	b	b₁	b₂	t	Type	h₂
06	250	155	1060	280	160	150	Guazigong	168.2

	h	h₁	h₂	b	b₁	b₂	t	t₁	Type	h₃	t₂
05	180	80	80	310	230	160	297	150	Jiaohudou	35.4	26.6

	h	h₁	h₂	b	b₁	b₂	t	Type
04	190	80	75	295	200	160	280	Sandou

	h	h₁	b	b₁	b₄	b₂	h₂	h₃	t	Type	b₃
03	240	140	1160	220	220	155	155	155	155	Huagong	159.1

	h	h₁	b	b₁	b₂	t	Type	h₂
02	240	140	1160	220	155	155	Nidaogong	159.1

	h	h₁	h₂	b	b₁	b₂	t	t₁	Type	h₁	t₂
01	310	110	120	550	395	155	560	155	Ludou	63.4	126.9

(**b**)

Figure 13. The experimental process: (**a**) the experimental specimen; (**b**) experimental data and their relationships.

The HBIM model for this dou-gong was established using the proposed method and program. The entire process is schematically illustrated in Figure 13b. The components were constructed from the bottom to the top, as mentioned above. The model of each component was automatically established and then manually assembled with previously-built components (left side of Figure 13b). A table is given on the right side of Figure 13b with four pieces of information, which are the information for measured visible parameters (black fonts), parameters passing through adjacent components (blue fonts), identification results of the component type (green fonts), and the deduced invisible parameters (red fonts). It should be noted that the component type and invisible parameters were intelligently and automatically determined through the method described above. The transfer relationships between the shared parameters of the adjacent components were introduced using the gray arrow lines. Two types of information were given as the input parameters (i.e., the measured visible parameters and the passed parameters), including the name and value of each parameter. The model for each component, except shuatou, was automatically established. Subsequently, the models of all the components in this dou-gong were manually assembled. It is worth stating that the entire process took only five minutes, and negligible manual intervention was required.

4.2. Application of the Modeling Method in Yingxian Wood Pagoda

The HBIM model of the renowned Yingxian Wood Pagoda was established based on 2D drawings to further validate the feasibility of the proposed method in actual engineering practice. As mentioned earlier, Guixiang Wang obtained the most comprehensive data of Yingxian Wood Pagoda in 1991. A full set of 2D drawings for each component, such as dou-gong, columns, and beams were used to present the dimensions of the visible components and the connection relationships of each component. The drawings of three types of dou-gong and their floors are presented in Figure 14.
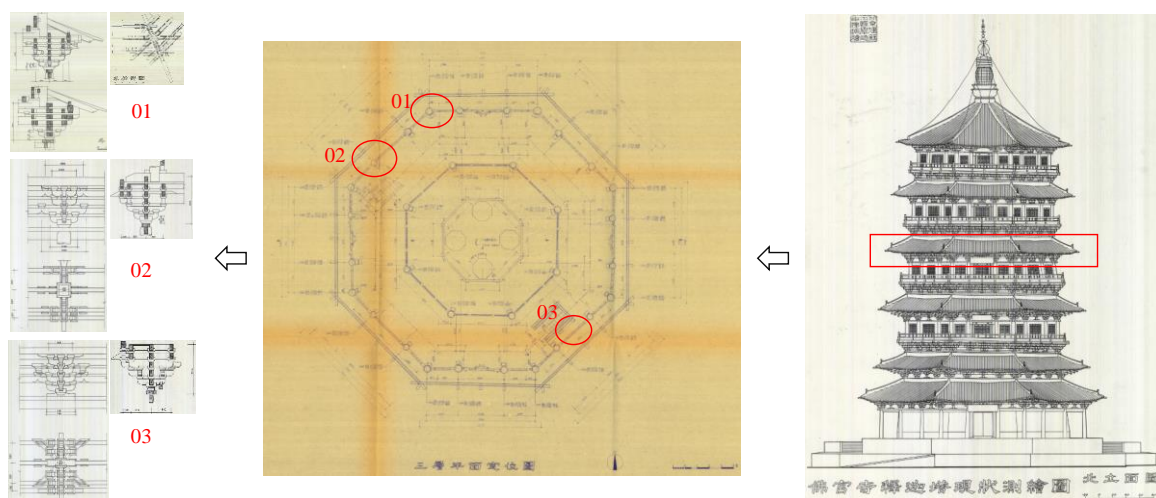

Figure 14. Drawings contain the surveying and mapping work of Yingxian Wood Pagoda.

The fundamental concept, i.e., from the component to the floor and from the floor to the entire structure, was implemented in the entire modeling process. In particular, the entire modeling process was divided into the following four steps as follows. (1) All the dou-gongs in the pagoda were established using the proposed method as elaborated in Section 4.1. The typical dou-gongs, which are consistent with those displayed in Figure 14, are presented in Figure 15a. (2) All the dou-gongs on each floor were assembled according to the 2D drawing of the floor. The beams and columns with simple appearances were manually established and assembled with the floor, leading to a single floor, as shown in Figure 15b. (3) All the floors were assembled, and the structure of the Yingxian Wood Pagoda was established, as presented in Figure 15c. (4) Finally, elements such as the decorative eaves,

windows, doors, and foundations were manually added to the structure, and the entire architecture was established, as shown in Figure 15d.
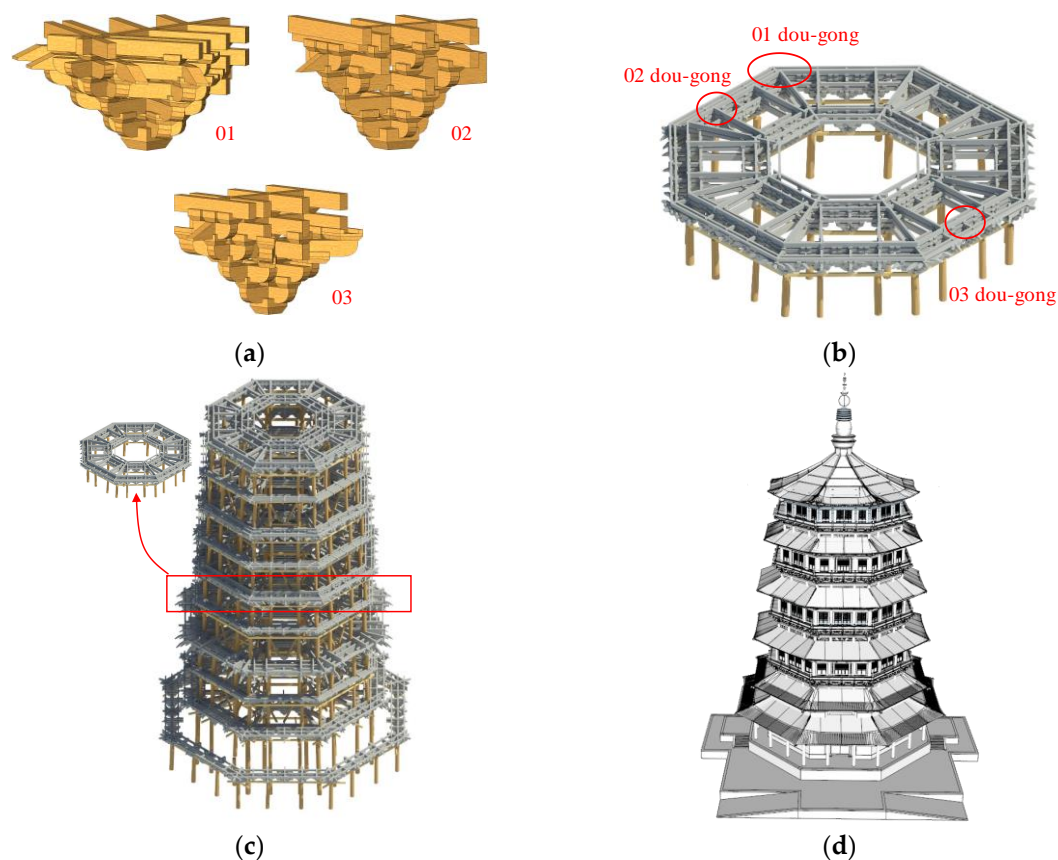

Figure 15. Establishment of the heritage/historic building information modeling (HBIM) model of Yingxian Wood Pagoda: (**a**) dou-gong; (**b**) floor; (**c**) structure; (**d**) architecture.

5. Conclusions

A parametric model of the typical components of an ancient wooden architectural structure with emphasis on commonality and characteristics, as well as an intelligent automated method for modeling these components, are two critical issues in the protection of such structures using HBIM.

Using a Chinese AWA building constructed during the Liao and Song dynasties as an example, a parametric model for the typical components with emphasis on commonality and characteristics were first proposed. Subsequently, an intelligent automated modeling method was developed and programmed using *Dynamo*. *Dynamo* can intelligently identify the component type and determine the invisible dimensions based on only the measured visible dimension, which is driven by the knowledge highlighted above. Additionally, *Dynamo* is capable of automatically establishing the corresponding HBIM model. A complicated dou-gong was established with surveying data using this method, thus validating the reliability and efficiency of the proposed method. Furthermore, the method was conclusively used to establish the HBIM model of Yingxian Wood Pagoda. The research findings will be a vital reference for the conservation of wooden architectural heritage structures.

It should be recognized that the actual conditions of AWA structures are complex. In particular, the damage of components was not considered in this study. Further improvements are required for considering the damaged components in future investigations.

Author Contributions: Yonghui Jiang conducted the entire research process and wrote the paper; Aiqun Li proposed the framework of the parametric model for typical components; Linlin Xie conceived the concept of the entire research process and guided the students to complete the research; Miaole Hou checked the 2D drawings;

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