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Parametric 3D reconstructing and interpreting iconographic evidence: case of the Song Dynasty architectural massing typologies

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Parametric heritage 3D reconstruction using iconographic evidence has the potential to extend modelling data sources and enhance the modelling efficiency. This study presents a novel and preliminary workflow to document, 3D reconstruct and interpret architectural massing typologies in the Song Dynasty of ancient China, integrating iconographic evidence. Multi-source historical images are collected and screened through chronological and appraisal assessments. The extracted massing principles are translated into parametric algorithms using Rhino-Grasshopper, then tested on 3D reconstruction of historical images by student participants. Furthermore, it is applied in an interactive design way through the Biomorpher plugin. The results show that the algorithms successfully enhanced the modelling efficiency, while limitations are also reflected. The interactive design application facilitates scenario comparisons in Song architecture 3D reconstruction and design. This study also sheds light on future applications in architectural conservation, interactive heritage education, and other research aspects in art and architecture.

3D reconstruction is considered a key procedure in architectural heritage research, conservation and interpretation. The accuracy of 3D reconstruction relies on synthesising multi-source evidence[1–3], from quantitative data like photogrammetry[4,5], remote sensing[6], to qualitative documentation like archaeological reports[7], photographs[8], archival documentation[9], oral histories[10], etc. Among these, the iconographic evidence from historical images, such as architectural drawings[11–13] and ancient paintings[14], is invaluable, especially when physical remains are scarce[3,15,16].

To enhance the efficiency of 3D modelling, parametric tools have proven effective from modelling architectural forms[17,18], to designing artefacts[19] and patterns[20–23]. By encoding architectural logic, such as shape grammars, into mathematical formulas or algorithms, these tools facilitate rapid generative modelling[24–27]. Platforms like Rhino-Grasshopper offer interfaces for graphical programming, and can be easily integrated with systems like HBIM (Heritage Building Information Modelling) and HGIS (Historical Geographic Information System), performing optimisation functions[28–31].

Parametric 3D reconstruction based on iconographic evidence has been explored in many studies recently[15,32]. Despite some advancements, integrating iconographic data sources systematically into heritage conservation requires expertise in iconography, architecture theory and digital modelling. Such an interdisciplinary task faces challenges in knowledge communication, collaboration, and time constraints[19,33]. Meanwhile, inaccuracies in each step can affect the authenticity of modelling results. For example, images from incorrect periods or imitation copies might be misused when lacking the capacity to evaluate iconographic evidence[34]. As suggested in the London Charter for the Computer-Based Visualisation of Cultural Heritage, computer visualisation should systematically identify and evaluate sources, and its dissemination should be accessible to a maximum range of users for cultural heritage learning and protection purposes[35].

This study focuses on the application of parametric 3D reconstruction on iconographic evidence, taking the Song Dynasty architectural massing typologies as a case study. In Chinese traditional architectural conservation, the surviving architecture and archaeological remains, often missing information of previous upper structures, could be insufficient for a comprehensive 3D reconstruction[36]. Historical images complement these data sources by offering contemporaneous visual documentation of architectural forms[37–39], and

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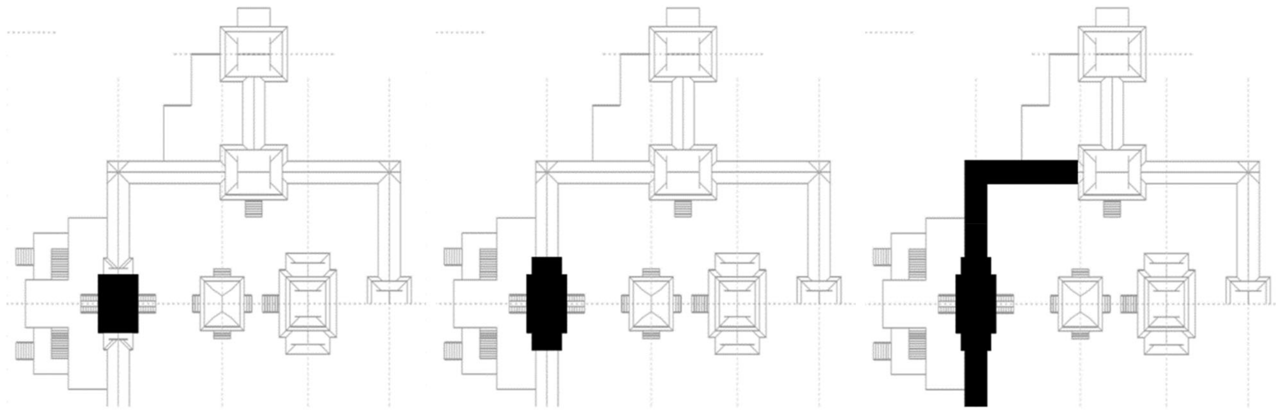


Fig. 1 | Illustration of Song architectural massing typologies. This figure shows the massing typology of *Xie Wu*, growing from the main building volume, and combing with *Lang*, adapted from ref. 77. **a** Main building volume; **b** Main building volume + *Xie Wu*; **c** Main building volume + *Xie Wu* + *Lang*

can serve as references for 3D reconstruction and interpretation if properly analysed[15]. As a period with typical architectural form and standardisation achievements, exemplified by the publication of *Yingzao Fashi* ("*Building standards*", "营造法式" in Chinese), the Song Dynasty offers insights into ancient architectural design principles[40,41]. One of these impactful design principles that was handed down by the following dynasties was the "architectural massing typologies"[39,42,43], referring to the correlative relationships between the main volume (正屋) and its affiliation volumes[44] (Fig. 1). Different typologies can be found in a small number of existing buildings and archaeological sites, while hardly mentioned in *Yingzao Fashi* (e.g. "Xie Wu 挟屋", "Lang 廊", "Guitou Wu 龟头屋") and other Song Dynasty texts (e.g. "Bo Shui 泊水"). "*Xie Wu (*挟屋*)*", "*Bo Shui (*泊水*)*" and "*Lang (*廊*)*" are three typical massing typologies.

Recent iconographic studies of Chinese traditional architecture were mainly historical studies[45–47], with minimal attention to bridging iconographic evidence with parametric heritage documentation, 3D reconstruction, and interpretation. Some other research for 3D reconstructing Chinese traditional architecture mainly relies on the *Yingzao Fashi* principles, which don't always explain the case-specific facts. Existing studies have also explored parametric modelling for Chinese traditional architecture, such as relying on textual frameworks from *Yingzao Fashi*[48–51], and *Gongcheng Zuofa Zeli (*工程做法则例*)*[51,52]. Recent works also investigated the composition and design principles of Qing courtyard buildings (四合院)[53], Hutongs (胡同)[54], roof tile components[55], and even modern architecture[56]. For extracting, documenting, and parametric modelling the design principles of Song Dynasty architectural massing typologies revealed from historical images, there is still a gap. Therefore, this study develops a workflow and algorithms that can support heritage professionals and even non-experts to generate efficient and authentic 3D reconstruction models under different research, learning, or design scenarios.

Methods

The selection of multi-source Song Dynasty images based on chronological and appraisal assessment

Multi-source Song Dynasty images open data that illustrate architectural massing typologies, ranging from paintings, images in local records and inscriptions on stone, to images in architectural decorations are exhausted (Data collection end-date: 18/04/2023) and collected in this study, which forms the main part of the evidence database. Non-image information shown in *Yingzao Fashi*, other textual documentation, and existing architectural cases and sites are also gathered as dual proof. There are 363 paintings, 38 images from local records and inscriptions from stone, 9 cases from other art forms, as well as textual and existing cases are collected as information resources of Song Dynasty architectural massing typologies (Fig. 2).

The selection of the retrieved images undergoes chronological and painting appraisal assessment, based on theories from scholars as Xu[34], Fu[38], publications from the Chinese Ancient Calligraphy and Painting Appraisal Group[57], and Cahill[58]. In Table 1 shows the assessment criteria and coding standard.

- The chronological and appraisal accuracies of the images are categorised into four grades (Very High, High, Medium, and Low).
- The levels of representation of the images are categorised into four grades (Very High, High, Medium, and Low). The chronological and appraisal assessment ensures that the information from images is authentic and reliable, avoiding the misuse of imitation/fake image versions. Only cases with at least medium accuracy and medium level of representation are used as evidence.
- The architectural massing typologies and typical characteristics of the structure and form that appeared in the images are also coded.

This study takes three important typologies, "*Xie Wu*", "*Bo Shui*" and "*Lang*" as main modelling cases. The "*Xie Wu*" refers to smaller parallel volumes connected to the left/right or both sides of the main building volume, following down-grade principles. The "*Bo Shui*" means a parallel affiliation volume connected to the front or back side of the main building volume. The "*Lang*" is a type of connecting volume used as corridors or boundaries in the design of courtyards. They represent three main logics in Song Dynasty architecture design, respectively, compositing building volumes from the axes of width and depth directions, and as linear connections. There are 119 cases collected that consist of typologies of "*Xie Wu*", 41 cases of "*Bo Shui*" and 153 cases of "*Lang*". After the chronological and appraisal assessment, the remaining evidence cases for the 3 typologies are: 104 cases for "*Xie Wu*", 40 cases of "*Bo Shui*" and 146 cases for "*Lang*" (Fig. 2).

Massing principles extraction and translation using Rhino-Grasshopper modelling

The Rhino-based Grasshopper plug-in is a graphical programming software that has been widely used in architectural design, urban planning, structural calculation, and heritage documentation, which can automatically generate digital models based on defined parameters and algorithms[30,53,59–61].

This study extracts and translates the massing principles shown in iconographic evidence. Focusing solely on the scale of building groups and their relationships, rather than on building details, this study only includes parameters that reflect these key characteristics. As some of the characteristics of affiliation volumes follow correlative principles with the main volume, the algorithms in this study are divided into two parts: the basic algorithms and the correlative algorithms.

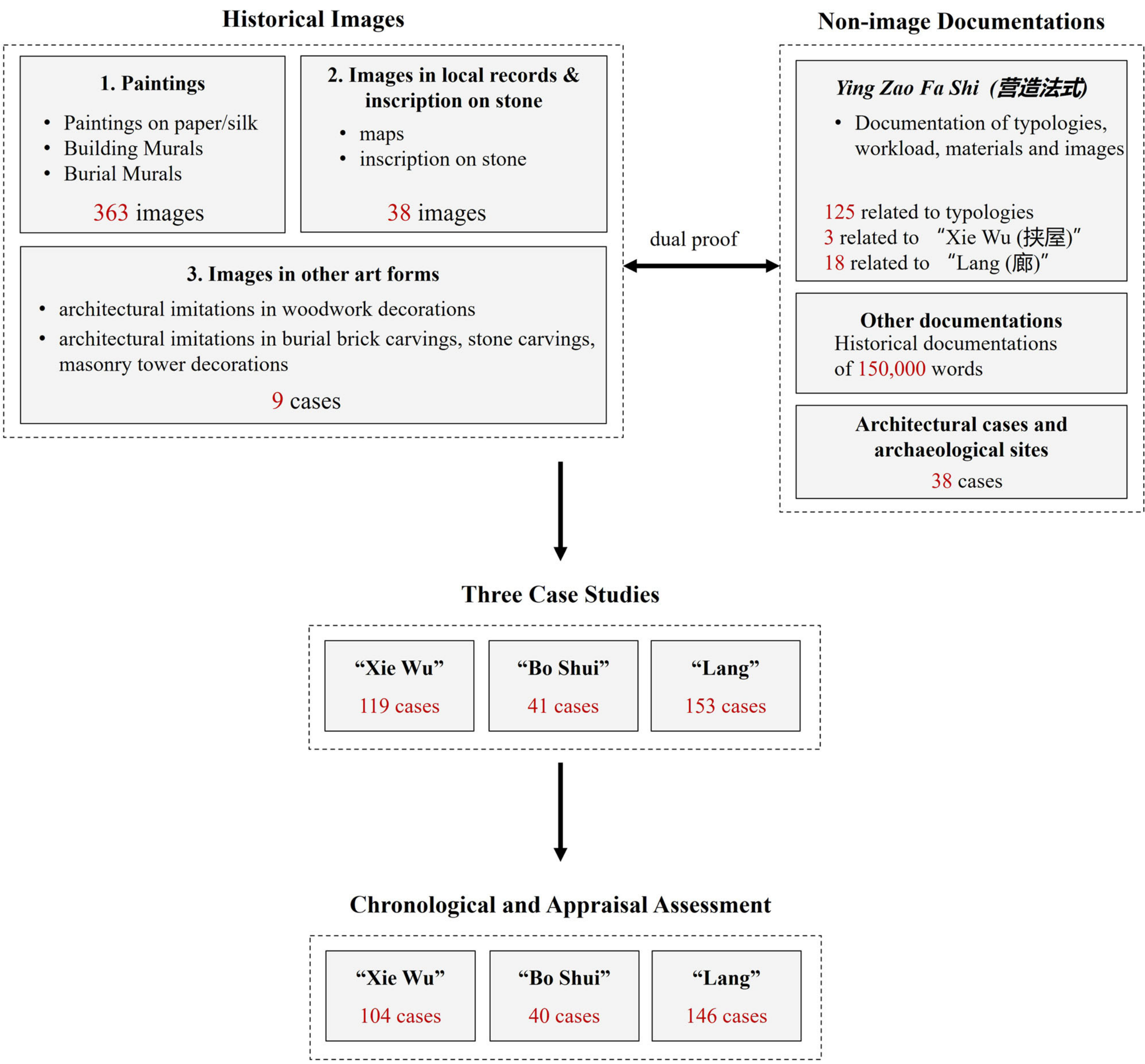


Fig. 2 | The retrieving and screening of historic information of Song Dynasty architectural massing typologies. This figure illustrate the categories of data sources, the dual proof approach, the selection of three typology cases, and the screening result.

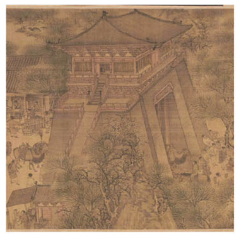
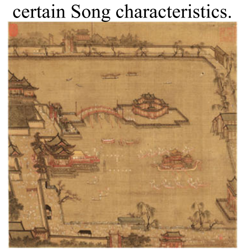
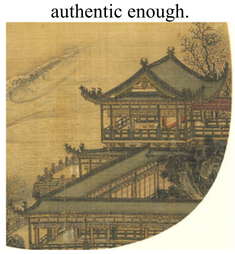
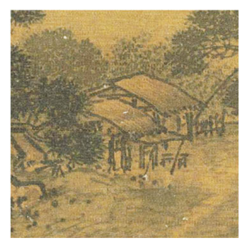
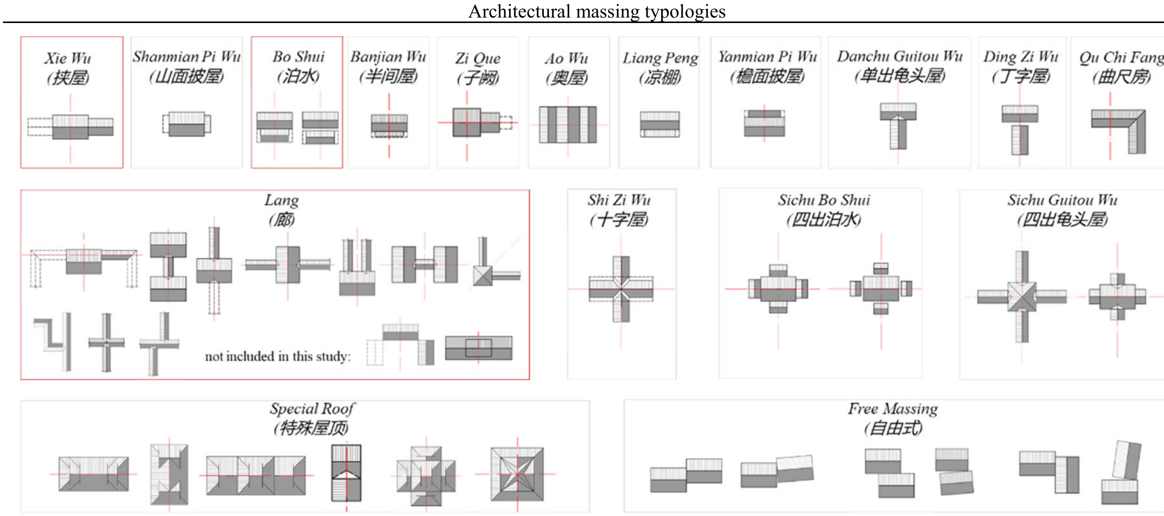
- Basic algorithms include the characteristics of a single building volume. These principles have been shown in fruitful studies by Liang[40,62], Pan and He[41], and Chen[63]. Previous studies have also shown the potential of translating principles from *Yingzao Fashi* into algorithms[48–51].
- Correlative algorithms include the characteristics in the affiliation volumes that might be the same as, be following a downgrade principle, or be independent of the main volumes. The related parameters and principles of "*Xie Wu*", "*Bo Shui*" and "*Lang*" have not yet been fully studied, so the extraction in this study also contributes to the history and theories of Chinese traditional architecture.

The whole algorithms follow the structure of "input parameters", "computation - control points and control lines", and "output - generated 3D building volumes"[49,53]. Parameter groups range from ground plan & scale, roof shape, to components. We define one parameter for the massing typology selection, and select 24 parameters of basic algorithms and 24 parameters of correlative algorithms to describe the design principles of three massing typologies (Table 2, Fig. 3). Within the correlative algorithms, there are 15 parameters for "*Xie Wu*", 12 correlative parameters for "*Bo Shui*", and 11 correlative parameters for "*Lang*" that need independent input. By embedding correlative principles in the algorithm, there are respectively 9, 10, and 6 parameters in the algorithms of "*Xie Wu*", "*Bo Shui*", and "*Lang*" that are controlled by the input from the main volume parameters. This means the percentages of reducing independent inputs are respectively 37.5%, 45.5%, and 35.3% in modelling each massing typology, which is expected to improve the modelling efficiency. Meanwhile, the algorithms embed all combination possibilities of different parameters, and allow creating scenarios of non-discovered typologies that follow the principles. In Fig. 3, a more detailed modelling flowchart illustrates the algorithm structure and the mutual influences between parameters.

Main building volume modelling

Referring to previous research on Song Dynasty architecture, we complete the modelling of the main building volume (Fig. 3, grey blocks).

Table 1 | The chronological and appraisal assessment process of historical images.

Chronological and appraisal accuracies			
Very High	High	Medium	Low
The painting itself fully reflects the information of the era, with e.g. the author's own inscriptions. There is a doubtless conclusion of the dating.	The painting reflects the information of the era. There is a generally accepted conclusion of dating.	The information on the painting is not enough for appraisals, but there is a rough consensus on the painting's period/dynasty. Some paintings from the dynasties around the Song Dynasty are also considered by scholars to reflect certain Song characteristics.	It is difficult to find enough evidence for the dating, and even scholars have different opinions.
			
Thousands of Miles of Mountains and Rivers (千里江山图), Northern Song Dynasty, Wang Ximeng, Palace Museum	*Along the River During the Qingming Festival (清明上河图)*, Northern Song Dynasty, Zhang Zeduan, Palace Museum	*Competition for the Gold Bright Pond (金明池争标图)*, Song Dynasty, Zhang Zeduan, Tianjin Museum	*Luoyang Tower (洛阳楼图)*, Tang Dynasty (others believe Yuan, Ming, Qing Dynasty), Li Zhaodao, National Palace Museum, Taipei
Levels of representation			
Very High	High	Medium	Low
The depiction reflects high degree of authenticity of architectural information.	The depiction reflects high degree of authenticity of architectural information, but the details of architectural components are not authentic enough.	The depiction of architectural information is simplified, but the basic scale of the building form can still be recognised.	The depiction of building forms cannot be identified, and only the number of building volumes can be roughly judged.
			
Scholars in Landscape (高士图), Five Dynasties and Ten Kingdoms period, Wei Xian, Palace Museum	*Watching the Tide at Night (月夜看潮图)*, Song Dynasty, Li Song, National Palace Museum, Taipei	*Album of Paintings Inscribed by the Emperor (宋帝命题册)*, Southern Song Dynasty, Ma Yuan, private collection	*Fishing Village by the Pines and Peaks (松岫渔村图)*, Southern Song Dynasty, Gao Keming, National Palace Museum, Taipei
Architectural massing typologies			
			

This table shows the assessment criteria and coding standard, respectively in chronological and appraisal accuracies, levels of representation, and the classification of architectural massing typologies. The source of digital scans of historical paintings are downloaded from the "Zhonghua Zhenbao Guan" (中华珍宝馆) platform.

Table 2 | The structure and organisation of input parameters in the algorithms

Parameter group	Basic algorithm	Correlative algorithm	Main building volume (正屋)	Xie Wu (挟屋)	Bo Shui (泊水)	Lang (廊)
typology	select massing typology					
ground plan & scale	central control point/line	relationships with central control point/line	√	🟩	🟩	√
	building type	relationships between building types	√	🟩	🟩	⬛
	Diantang ground plan	relationships between Diantang ground plans	√	√	√	⬛
	Tingtang ground plan	relationships between Tingtang ground plans	√	√	√	√
	width [Jian (间)]	relationships between widths	√	√	√*	√
	depth units [Chuan (椽)]	relationships between depth units	√	√*	√	√*
	Cai/Fen/Zhi (材/分/栔)	relationships between Cai/Fen/Zhi	√	🟩	🟩	🟩
	width between pillars (柱距) [Fen (分)]	relationships between widths between pillars	√	√	🟩	√
	depth per unit (架深) [Fen (分)]	relationships between depths per unit	√	√*	√	√
	eaves pillars height (檐柱高) [Fen (分)]	relationships between eaves pillars height	√	√*	🟩	√
		volume relationship	⬛	√	⬛	⬛
		structure relationship	⬛	√	√	⬛
		volume side	⬛	√	√	⬛
roof shape	roof type	relationships between roof types	√	🟩	√	⬛
	number of floors	relationships between number of floors	√	√*	√*	⬛
	eave layers	relationships between eave layers	√	√	⬛	⬛
components	Juzhe (举折)	relationships between Juzhe	√	🟩	🟩	🟩
	pillar diameter (柱径) [Fen (分)]	relationships between pillar diameters	√	🟩	🟩	🟩
	rafter diameter (椽径) [Fen (分)]	relationships between rafter diameters	√	🟩	🟩	🟩
	purlin diameter (槫径) [Fen (分)]	relationships between purlin diameters	√	🟩	🟩	🟩
	purlin extension (出际) [Chi (尺) Cun (寸)]	relationships between purlin extensions	√	🟩	🟩	🟩
	bracket sets (铺作层数)	relationships between bracket sets	√	√*	√	√*
	intercolumnar bracket sets (补间铺作)	relationships between intercolumnar bracket sets	√	√	√	√
	bracketing of Fujie (副阶铺作层数) [Pu (铺)]	relationships between bracketing of Fujie	√	√	⬛	⬛
	walls		⬛	⬛	√	⬛
	wall type		⬛	⬛	⬛	√
	wall location		⬛	⬛	⬛	√
sum	24	24	21	24	22	17
"√(*)"			21	15	12	11
"🟩"			-	9	10	6
reduced independent input (%)			-	37.5%	45.5%	35.3%

√ Independent input free parameters
√* Independent input parameters influenced by the main volume
🟩 Parameters controlled by main volume
⬛ Such parameter doesn't exist for this massing typology

- A "central control point of the main volume" is linked to the Rhino model.
- For the ground plan parameters, it can be chosen from "Diantang *(殿堂)*" to "Tingtang *(厅堂)*" typologies. Then, more detailed values of the column grid can be selected.
- For the scale parameters, the main measurement unit, "Cai *(材)*", is defined. Then the "width *(开间)*", "depth units *(进深)*" and "eaves pillars height *(檐柱高)*" of the main building volume, as well as the partitioning parameters such as "width between pillars *(柱距)*", "depth per unit *(架深)*" are defined. These parameters all follow the measurement unit of Cai.
- For the roof shape parameters, there are three inputs: "roof type" (including 3 main types, "hip-gable *(歇山)*", "two-sloped-gable *(悬山)*" or "hip roof *(庑殿)*"), "number of floors", and the "eave layers" (including 2 types, "single eave *(单檐)*" or "double eaves *(重檐)*").
- For the components parameters, the "Juzhe *(举折)*" can be influenced by the "building type". The other 5 parameters, "pillar diameter *(柱径)*", "rafter diameter *(椽径)*", "purlin diameter *(槫径)*", "purlin extension *(出际)*", and "bracket sets *(斗栱)*" follow the measurement unit of Cai.
- For all parameters mentioned in *Yingzao Fashi* and previous research, we provide recommended values, but there can be flexible inputs on a case-by-case basis.

The algorithms of "computation - control points and control lines" and "output - generated 3D building volumes" are internal codes that can run automatically. They include the control points/lines of the building "Ceyang *(侧样)*" based on the input of ground plan & scale, roof shape, and components parameters, along with the bracket sets control point/lines based on the input of bracket set parameters. Finally, the main building volume includes the "walls & openings", "foundation platform *(台基)*", "pillars", "rafters", "purlins", "roof & roof ridges", and "bracket sets".

Following the input of the main building volume, architectural massing typologies can be chosen. In this study, we preliminarily provide 5 options, none (single volume), "*Xie Wu*", "*Bo Shui*", "*Xie Wu* + *Bo Shui*", and an on/off button of "*Lang*" (Fig. 3, purple block).

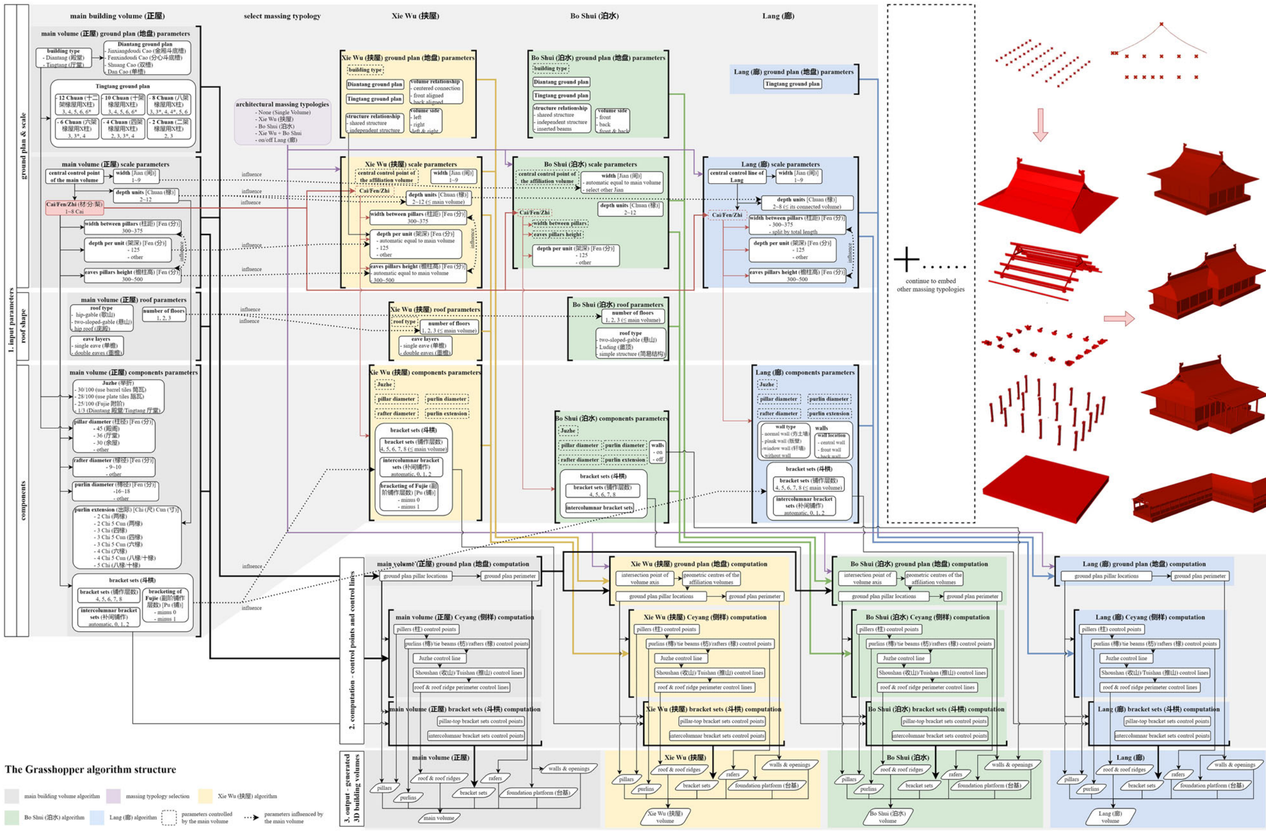


Fig. 3 | The Grasshopper algorithm structure. The flow chart illustrates the parameters, options or input range of each parameter, and the relationships and mutual influence between parameters.

"Xie Wu" parametric modelling

According to the previous study of "*Xie Wu*" correlative principles[44] and related parameters defined in this study (Table 2), the algorithms are categorised into three groups (Fig. 3, yellow blocks, Table 3).

1. Parameters controlled by the main volume. These characteristics are directly consistent with the main volume and are not allowed to change on their own initiative. For example, "*Xie Wu*"'s "building type" of "Diantang" or "Tingtang" follows the input parameter of the main building volume[44]. According to *Yingzao Fashi*, the "Cai" of "*Xie Wu*" is one grade lower than the "Cai" of the main volume, so this parameter is also controlled by the main volume. Similarly, the roof type of the "*Xie Wu*" usually follows that of the main volume.
2. Independent input parameters influenced by the main volume. The number of "depth units" and the "depth per unit" of the "*Xie Wu*" are under certain constrains from the main volume. For example, the number of "depth units" should be less than or equal to the main volume's "depth units". The value of "depth per unit" also depends on the mutual "structure relationship" and "volume relationship" between the main and affiliation volumes. When there is a shared structure, the values are equal. In many cases, the "eaves pillars height" stays equal between the main and affiliation volumes. The layer of "bracket sets" in the "*Xie Wu*" usually lower the grade, too, so this value should be less than that in the main volume.
3. Independent input free parameters. For some parameters of the "*Xie Wu*", like "structure relationship", "volume relationship", "volume side", and "width between pillars", the values are not subjected to the main volume, so they can be freely selected by users according to the specific objectives.

"Bo Shui" parametric modelling

Similar to "*Xie Wu*", the correlative principles and related parameters of "*Bo Shui*" (Table 2) can also be categorised (Fig. 3, green blocks, Table 4).

1. Parameters controlled by the main volume. Due to the affiliation volume in the "*Bo Shui*" massing typology being adjacent to the front or back side of the main building volume, some parameters of "*Bo Shui*", such as the "building type", "Cai", "width between pillars, and "eaves pillars height" are usually the same as those from the main volume.
2. Independent input parameters influenced by the main volume. Some parameters like the "number of floors" can be influenced by the main volume, often having the same values.
3. Independent input free parameters. Parameters like "structure relationship", "volume side", "depth units", and "roof types" are independent input parameters.

"*Lang*" parametric modelling

The modelling of *Lang* is based on a central control line, which allows the construction of linear volumes. Compared to "*Xie Wu*" and "*Bo Shui*", the correlative principles of "*Lang*" with the main building volume are less obvious (Table 2). According to *Yingzao Fashi*, the "Cai" of "*Lang*" is two grades lower than the "Cai" of the main volume, which is the main characteristic controlled by the main volume (Fig. 3, blue blocks, Table 5). We also provide several options for modelling the partition walls shown in the cases, including the "wall type" and the "wall location".

Validation and application of the massing principles

After building the algorithms, a validation and application process is conducted. Using the Grasshopper algorithms, exercises on 3D reconstruction of historical images are conducted to test the capability

Table 3 | The relationship between selected parameters, evidence sources, and their integration into the "*Xie Wu*" algorithm

Correlative algorithm	Xie Wu (挟屋)	Evidence examples	Algorism realisation
relationships with central control point/line	■	-	automatic calculated
relationships between building types	■	*Yingzao Fashi*	same
relationships between Diantang ground plans	√	Not yet a specific rule observed	free input
relationships between Tingtang ground plans	√	Not yet a specific rule observed	free input
relationships between widths	√	Not yet a specific rule observed	free input
relationships between depth units	√*	*murals of Yanshan Temple in Fanzhi, Shanxi (山西繁峙岩山寺壁画)* *Incense Burning Ceremony (焚香祝圣图)* *Landscapes of the Four Seasons (四景山水图)* *Thousands of Miles of Mountains and Rivers (千里江山图)* *Banquet by Lantern Light (华灯侍宴图)*	≤ main volume
relationships between Cai/Fen/Zhi	■	*Yingzao Fashi*	one grade lower than the Cai of the main volume
relationships between widths between pillars	√	Not yet a specific rule observed	free input
relationships between depths per unit	√*	*Pavilion and Landscape (楼阁山水图)*	- automatic equal to main volume - 125 - other
relationships between eaves pillars height	√*	*"正殿五间，朵殿二间，……柱高丈五尺。" see Zhou, Bida (the Southern Song Dynasty) Si Ling Lu (思陵录)* *Autumn in Han Palace (汉宫秋图)*	- automatic equal to main volume - 300~500
volume relationship	√	*Weinan Chanxiu Temple Daxiongbao Hall (渭南禅修寺大殿)* *Snow at Dusk over Mountains and Streams (溪山暮雪图)*	- centered connection - front aligned - back aligned
structure relationship	√	*Water Mill (闸口盘车图)* *murals of Yanshan Temple in Fanzhi, Shanxi (山西繁峙岩山寺壁画)* *Weinan Chanxiu Temple Daxiongbao Hall (渭南禅修寺大殿)* *Pavilion and Landscape (楼阁山水图)*	- shared structure - independent structure
volume side	√	*Thousands of Miles of Mountains and Rivers (千里江山图)* *Banquet by Lantern Light (华灯侍宴图)* *murals of Yanshan Temple in Fanzhi, Shanxi (山西繁峙岩山寺壁画)*	- left - right -left & right
relationships between roof types	■	*Courtly Odes, Beginning with Wild Geese (诗经・小雅・鸿雁之什图)* *Water Mill (闸口盘车图)* *Delicate Residence at Songdeng (松磴精庐图)* *Thousands of Miles of Mountains and Rivers (千里江山图)* *murals of Yanshan Temple in Fanzhi, Shanxi (山西繁峙岩山寺壁画)*	same
relationships between number of floors	√*	*murals of Yanshan Temple in Fanzhi, Shanxi (山西繁峙岩山寺壁画)* *Spring Dawn in the Lake and Mountains (湖山春晓图)* *Competition for the Gold Bright Pond (金明池争标图)*	≤ main volume
relationships between eave layers	√	Not yet a specific rule observed	free input
relationships between Juzhe	■	Cannot be extracted from images, but recommended values are provided according to *Yingzao Fashi*	same
relationships between pillar diameters	■		
relationships between rafter diameters	■		
relationships between purlin diameters	■		
relationships between purlin extensions	■		
relationships between bracket sets	√*	*Water Mill (闸口盘车图)* *murals of Yanshan Temple in Fanzhi, Shanxi (山西繁峙岩山寺壁画)* *Autumn in Han Palace (汉宫秋图)*	≤ main volume
relationships between intercolumnar bracket sets	√	Not yet a specific rule observed	free input
relationships between bracketing of Fujie	√	Not yet a specific rule observed	free input

√ Independent input free parameters
√* Independent input parameters influenced by the main volume
■ Parameters controlled by main volume

Table 4 | The relationship between selected parameters, evidence sources, and their integration into the "*Bo Shui*" algorithm

Correlative algorithm	Bo Shui (泊水)	Evidence examples	Algorism realisation
relationships with central control point/line	■	-	automatic calculated
relationships between building types	■	*Main Hall (正殿) and Xian Hall (献殿) of Dou Daifu Temple (窦大夫祠)* *Pictures of Auspicious Omens (中兴瑞应图)*	same
relationships between Diantang ground plans	√	Not yet a specific rule observed	free input
relationships between Tingtang ground plans	√	Not yet a specific rule observed	free input
relationships between widths	√*	*Pictures of Auspicious Omens (中兴瑞应图)* *Baosha of Huozhoushu Main Hall (霍州署大堂前抱厦)* *Incense Burning Ceremony (焚香祝圣图)*	- automatic equal to main volume - select other Jian
relationships between depth units	√	Not yet a specific rule observed	free input
relationships between Cai/Fen/Zhi	■	*Main Hall (正殿) and Xian Hall (献殿) of Dou Daifu Temple (窦大夫祠)*	same
relationships between widths between pillars	■	*Pictures of Auspicious Omens (中兴瑞应图)*	same
relationships between depths per unit	√	Not yet a specific rule observed	free input
relationships between eaves pillars height	■	*Main Hall (正殿) and Xian Hall (献殿) of Dou Daifu Temple (窦大夫祠)* *Autumn in Han Palace (汉宫秋图)*	same
structure relationship	√	*Autumn in Han Palace (汉宫秋图)* *Pictures of Auspicious Omens (中兴瑞应图)* *Dragon Boats Racing for the Pennant (龙舟夺标图)*	- shared structure - independent structure - inserted beams
volume side	√	*Landscapes of the Four Seasons (四景山水图)* *"厅堂前后皆有瓦凉棚三间。" see Chen, Kui (the Southern Song Dynasty). Nan Song guan'ge lu (南宋馆阁录)*	- front - back - front & back
relationships between roof types	√	*Pictures of Auspicious Omens (中兴瑞应图)* *Autumn in Han Palace (汉宫秋图)* *Landscapes of the Four Seasons (四景山水图)* *Incense Burning Ceremony (焚香祝圣图)*	- two-sloped-gable (悬山) - Luding (盝顶) - simple structure (简易结构)
relationships between number of floors	√*	*Pavilions Amid Winter Trees (寒林楼观图)*	free input
relationships between Juzhe	■	Cannot be extracted from images, but recommended values are provided according to *Yingzao Fashi*	same
relationships between pillar diameters	■		
relationships between rafter diameters	■		
relationships between purlin diameters	■		
relationships between purlin extensions	■		
relationships between bracket sets	√	Not yet a specific rule observed	same
relationships between intercolumnar bracket sets	√	Not yet a specific rule observed	same
walls	√	*Along the River During the Qingming Festival (清明上河图)* *Pictures of Auspicious Omens (中兴瑞应图)*	- on - off

√ Independent input free parameters
√* Independent input parameters influenced by the main volume
■ Parameters controlled by main volume

of the algorithms. Four students from different backgrounds are asked to use the algorithms to 3D reconstruct the holistic architectural scenes from seven paintings, including building volumes and the surrounding environments. The final 3D reconstruction results they provided should be approved by at least one expert. They are also asked to count the number of minutes spent (including time of parametric modelling and time of manual adjustment), and reflect on the biggest challenge of 3D reconstruction.

For further application, the Biomorpher plugin in Grasshopper is used as an interactive optimisation interface for Song Dynasty architectural massing typologies design. This allows the generation of several alternative optimal solutions instead of inputting manually, and is able to evolve continuously to assist generative design.

Results

Parametric modelling outputs

The parametric modelling outputs show diverse combinations of different parameters. Part of the parameter combinations with 73 outcomes are illustrated (Fig. 4). It should be noted that only some obvious parameters are included in this table, such as the "roof type", "eave layers", "volume relationship", "structure relationship", and "control line" attributes. Parameters such as ground plan, and component dimensions are not shown in this table to reduce overwhelming information. If bringing the value variations of the non-listed parameters into the combinations, the number of outcomes that this algorithm provides can result in a dramatic increase.

Validation and effectiveness assessment

The parametric algorithms are tested through a 3D reconstruction process regarding Song Dynasty paintings by four student participants (Fig. 5), with time and challenges recorded. The selected paintings are 1) the western wall murals of *YanshanTemple in Fanzhi, Shanxi (山西繁峙岩山寺西壁壁画)*, 2) the painting *Incense Burning Ceremony (焚香祝圣图)*, 3) the painting *Delicate Residence at Songdeng (松磴精庐图)*, 4) the painting *Autumn Scenery of Rivers and Mountains (江山秋色图)*, 5) the painting *Palace banquet (乞巧图), 6) the*

Table 5 | The relationship between selected parameters, evidence sources, and their integration into the “*Lang*” algorithm

Correlative algorithm	Lang (廊)	Evidence examples	Algorism realisation
relationships with central control point/line	√	-	free input
relationships between Tingtang ground plans	√	Not yet a specific rule observed	free input
relationships between widths	√	Not yet a specific rule observed	free input
relationships between depth units	√ *	*Autumn Scenery of Rivers and Mountains (江山秋色图)*	⩽ its connected volume
relationships between Cai/Fen/Zhi	■	*Yingzao Fashi*	two grades lower than the Cai of the main volume
relationships between widths between pillars	√	Not yet a specific rule observed	free input
relationships between depths per unit	√	Not yet a specific rule observed	free input
relationships between eaves pillars height	√	Not yet a specific rule observed	free input
relationships between Juzhe	■	Cannot be extracted from images, but recommended values are provided according to *Yingzao Fashi*	same
relationships between pillar diameters	■		
relationships between rafter diameters	■		
relationships between purlin diameters	■		
relationships between purlin extensions	■		
relationships between bracket sets	√ *	*Water Mill (闸口盘车图)* *murals of Yanshan Temple in Fanzhi, Shanxi (山西繁峙岩山寺壁画)* *Autumn in Han Palace (汉宫秋图)*	≤ main volume
relationships between intercolumnar bracket sets	√	Not yet a specific rule observed	free input
wall type	√	*Summer Palace of the Ming emperor Figure (明皇避暑宫图)* *murals of Yanshan Temple in Fanzhi, Shanxi (山西繁峙岩山寺壁画)* *Palace banquet (乞巧图)* *Water Mill (闸口盘车图)* *Watching the Tide at Night (月夜看潮图)*	- normal wall (夯土墙) - plank wall (版壁) -window wall (轩墙) - without wall
wall location	√	*Summer Palace of the Ming emperor Figure(明皇避暑宫图)* *murals of Yanshan Temple in Fanzhi, Shanxi (山西繁峙岩山寺壁画)* *Palace banquet (乞巧图)* *Water Mill (闸口盘车图)*	- central wall - front wall - back wall

√ Independent input free parameters
√* Independent input parameters influenced by the main volume
■ Parameters controlled by main volume

*painting Pictures of Auspicious Omens (*中兴瑞应图*)*, and *7) the painting Eighteen Songs of a Nomad Flut (*胡笳十八拍*)* (Table 6).

3D reconstruction modelling efficiency highly depends on the content complexity of the referenced painting, the required accuracy of output, the participant’s academic knowledge and modelling skills. This makes it difficult to quantify the degree of optimisation of this approach compared to traditional 3D reconstruction. However, it can be confirmed that the efficiency has been significantly improved, based on the authors’ previous experience in Chinese Song Dynasty historical painting 3D reconstruction. The 3D reconstruction process usually consists of an identification process, including collecting references and background information, identifying typologies, speculating possible values of parameters, modelling, and adjustment and iteration. Usually, a painting including a series of building volumes takes days to weeks to reach essentially accurate outcomes. A worse situation is mentioned by the traditional modelling workflows of other types of architecture based on iconographic evidence[64].

Through the application of this algorithm, the modelling of each building volume can be completed around 15 min, and that for modelling all elements in one painting can be reduced to around 2.5 h. Particularly in the modelling of some regular and symmetrical courtyard spaces, the time can be as short as 15 min for completing both parametric modelling and manual adjustment (Table 7).

It is recognised by the participants that parametric modelling didn’t consume much time for only choosing from the pre-defined options for each input parameter, but more time was spent on adjusting the relative positions of different building volumes and comparing different output versions, to gradually increase the accuracy with the referenced 2D painting. Besides, the most time-consuming process is still the manual modelling of building volumes and surrounding environments that don’t have pre-defined algorithms. For example, the modelling of undefined building volumes intersection features is extremely difficult, as the current algorithm is not yet sufficient to address all variations of intersection details (Table 8).

Scenarios comparison using Biomorpher

As an extended application of the algorithms, the Biomorpher plugin in Grasshopper helps generate combinations of parameters, which can be used for design comparisons. Biomorpher can compute a set of 12 scenarios each time (Fig. 6). According to the actual needs of the design, evolution directions can be set, such as 1) the need to achieve the maximum use of space (largest volumes), 2) the need to achieve the most complex form (largest surface area), 3) the main and affiliation volumes have the same value of pillar heights, etc. As the evolutionary direction is determined, it will evolve to the best design as the number of generations increases. The use of Biomorpher extends the function of the algorithms to fulfil both research and design purposes.

Discussion

This paper presents a novel and preliminary study of developing parametric modelling workflows using Rhino-Grasshopper to document, 3D reconstruct and interpret Song architectural massing typologies, integrating iconographic evidence. First, multi-source historical

Fig. 4 | Examples of 3D reconstruction variations with multiple massing typologies. This figure shows respectively some key examples of parametric "*Xie Wu*", "*Bo Shui*", "*Lang*", and combinations modelling.

images are screened based on chronological and appraisal accuracies, and levels of representation. The extracted and translated principles result in algorithms that can realise a great amount of massing typology modelling by changing the combinations of values among 24 basic parameters and 24 correlative parameters. Second, a validation and application process is conducted to test the algorithm's effectiveness and robustness. There are 7 paintings successfully 3D reconstructed by student participants, meanwhile reflecting on the potential challenges. The Biomorpher plugin is also used to explore the application of this algorithm to serve for other architectural design and scenario-comparison tasks.

The current algorithms also have the following implementations and limitations:

- The massing typology principles are embedded in the Grasshopper algorithm, so that users need not input manually, which can also avoid false inputs. This can expand the scope of 3D reconstruction researchers, for example, from architectural scholars to public.

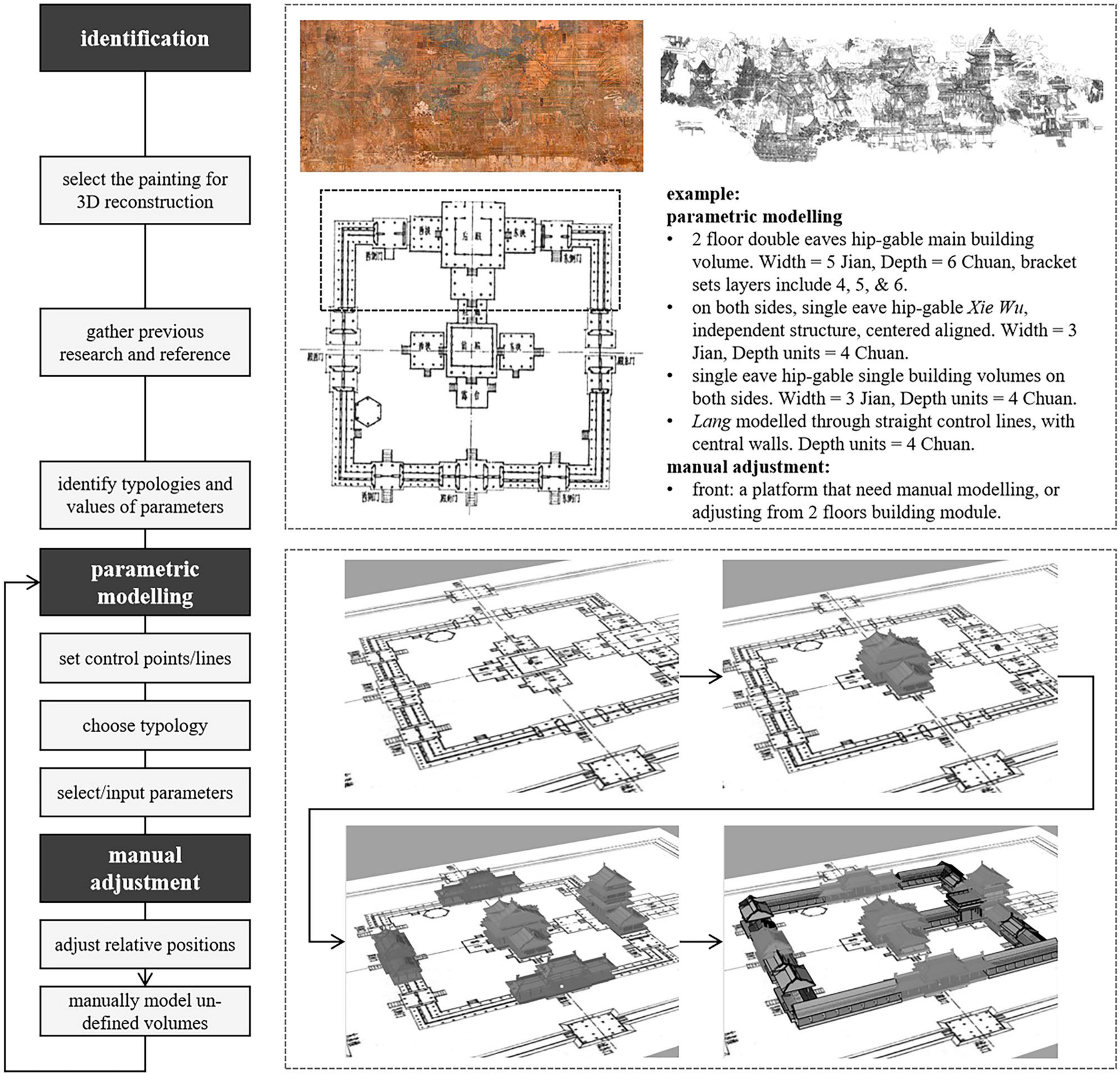
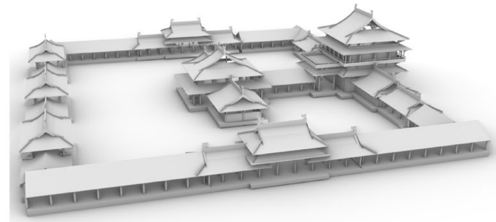
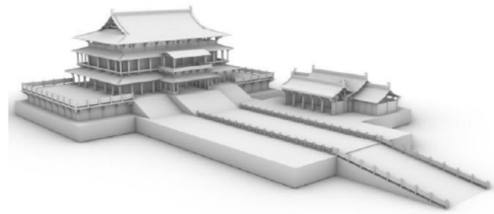
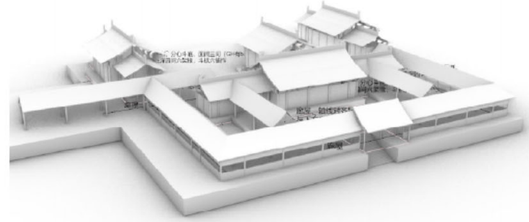
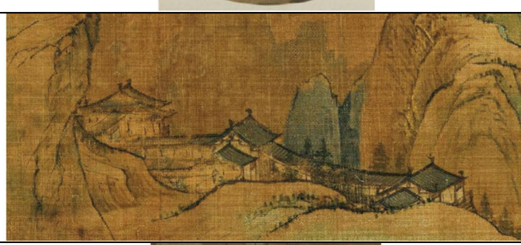
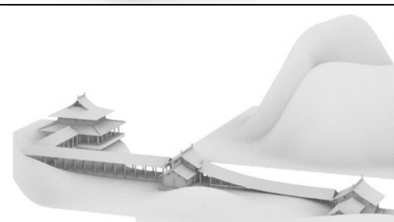
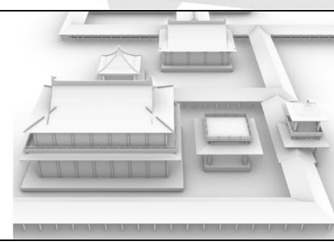
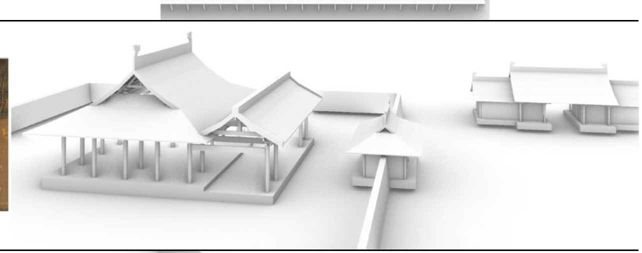
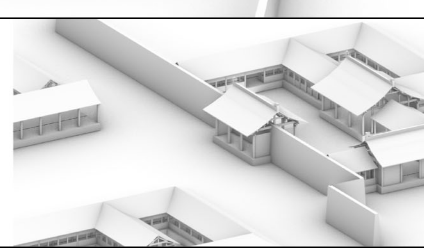


Fig. 5 | The workflow of 3D reconstruction of Song Dynasty painting engaging student participants. The workflow includes identification, parametric modelling, and manual adjustment.

- The typologies of "*Xie Wu*", "*Bo Shui*" and "*Lang*" typologies have been preliminarily researched and documented in this study. If more modules of architectural single volume algorithms and massing typologies algorithms are added to the existing algorithm, more elements from paintings can be automatically generated and reducing time. Future studies can explore other typologies and add to this database.
- This study only focuses on specific parameters in the scale of architectural massing typology, but not all parameters of Song Dynasty architecture. More basic and correlative parameters can be explored following the same workflow of extracting, translating, and parametric modelling, to provide more detailed models (e.g. spatial partitions inside the volumes, chronological changes of the characteristics within different periods of Song Dynasty, integrating with Song Dynasty courtyard layout and urban planning principles, etc.). It is also found more diverse form, structural, and spatial parameters are represented in different paintings, especially regarding volume conjunction point. Future optimisation of algorithms is expected.
- Currently, there is still a gap in heritage documentation, integrating both parametric and reality-based modelling[65]. To better empower research and 3D reconstruction of real sites, the algorithms in this study are welcome to be tested and optimised through implementation in Song Dynasty (and can be extended to Sui and Yuan Dynasty) archaeological sites. As the 3D reconstruction of 2D paintings also required more time to predict the volume relationships and enhance similarity with the paintings, 3D reconstruction conducted based on textual or archaeological evidence might take less time since they can tolerate relatively higher levels of speculation and have a clearer information of relative positions of different building volumes. Other challenges may occur related to specific types of reconstruction basis,

Table 6 | 3D reconstructing Song Dynasty paintings.

Painting	Original painting scene	3D reconstruction result
1		
2		
3		
4		
5		
6		
7		

The source of digital scans of historical paintings: 1 - Images collected independently by Tsinghua University; 2–7: downloaded from the "Zhonghua Zhenbao Guan" (中华珍宝馆) platform.

Table 7 | Time spent by each 3D reconstruction case

Painting	Participant	Architectural volume number	Total time (min)			Average time per volume (min)	
			Total	Parametric	Manual	Parametric	Manual
1	A	29	15	5	10	0.2	0.3
2	B	8	90	45	45	5.6	5.6
3	B	17	195	180	15	10.6	0.9
4	C	10	480	360	120	36.0	12.0
5	C	11	180	120	70	10.9	6.4
6	C	8	60	60	95	7.5	11.9
7	D	13	105	70	35	5.4	2.7
Average		13.7	160.7	120.0	55.7	10.9	5.7

Time of parametric modelling: includes the time identifying the typologies, selecting modules and parameters, and setting the parameters.
Time of manual adjustment: includes the time spent iterating for the best relative positions, modelling the surrounding environment, and modelling from scratch the volumes without corresponding parametric algorithms.
Architectural volume number: includes massing typology volumes, building volumes without corresponding parametric algorithms, and surrounding environment blocks.

Table 8 | Challenges in the 3D reconstruction process mentioned by each participant

Painting	Name of the painting	Participant	Academic background	Challenges in the 3D reconstruction process mentioned by the participant
1	*the western wall murals of Yanshan Temple in Fanzhi, Shanxi (山西繁峙岩山寺西壁壁画)*	A	Bachelor student in architecture design with basic knowledge of Rhino and Grasshopper modelling, and Chinese architecture theory	• It took more time to model the building volumes without corresponding algorithms. • Much more efficient when there's already a 3D reconstruction proposal conducted by previous scholars.
2	*Autumn Scenery of Rivers and Mountains (江山秋色图)*	B	Bachelor student in architecture design with basic knowledge of Rhino and Grasshopper modelling, and Chinese architecture theory	• It was quite easy for just choosing within the given parameters, while more time was spent on the iteration process of setting the control points/lines for each volume, adjusting relative positions, changing input parameters, in order to get closer to the original painting scenes. • It is difficult to automatically fit the topographical setting shown in the paintings, which requires long-time manual adjustment.
3	*Delicate Residence at Songdeng (松磴精庐图)*			
4	*Incense Burning Ceremony (焚香祝圣图)*	C	Master student in history with interest in Chinese traditional architecture, and with limited knowledge in Grasshopper modelling and no experience in Rhino modelling without Grasshopper	• Unable to model those building volumes without corresponding algorithms. • The undefined conjunction point modelling varied from different paintings, which the current algorithm is insufficient to address these characteristics and is dependent on manual adjustment. • The algorithms perform better in 3D reconstruction from textual and archaeological information, allowing more comparisons of parameter combinations.
5	*Palace banquet (乞巧图)*			
6	*Pictures of Auspicious Omens (中兴瑞应图)*			
7	*Eighteen Songs of a Nomad Flut (胡笳十八拍)*	D	Master student in architectural history and theory, with basic knowledge of Rhino and Grasshopper modelling	• The most challenging part lies in the comparison of different 3D reconstruction versions. • Especially time-consuming to define the relative sizes of connected volumes, choosing between different Cai, and different values of widths and depth.

for example, developing automatic modelling processes linking real-site data with theoretical principles, e.g. smart point clouds[66].

- It is also needed to discuss validation tools for ensuring the authenticity of output forms, which is to clarify the relationship between the output model and its evidence source, therefore enhancing articulation[35]. More advanced technologies can be used in chronological and appraisal assessment[67–69]. On one hand, since manual identification of architectural massing typologies is still a timely step in the current workflow, it is still needed to organise collaboration between professionals of art history and architectural conservation, to facilitate multi-disciplinary knowledge exchange and its implementation in real practice. On the other hand, artificial intelligence, e.g. machine learning[70,71], can be introduced to all steps of research, documentation, conservation and interpretation, such as massing typology identification, principles extraction, automatic documentation, and volume-intersection adjustment.
- This easy-input and real-time interface of Grasshopper also sheds light on other implementation directions, such as interactive heritage education[72], serious game scene design[73,74], cultural dissemination[75,76], etc, which expect future exploration.

In conclusion, this study bridges the gap between iconography of art history and architectural conservation in current practices, and has the potential to be implemented in real archaeological research, efficient 3D reconstruction and scenarios comparison. We provide a tool for heritage professionals to research, 3D reconstruct and interpret Song Dynasty

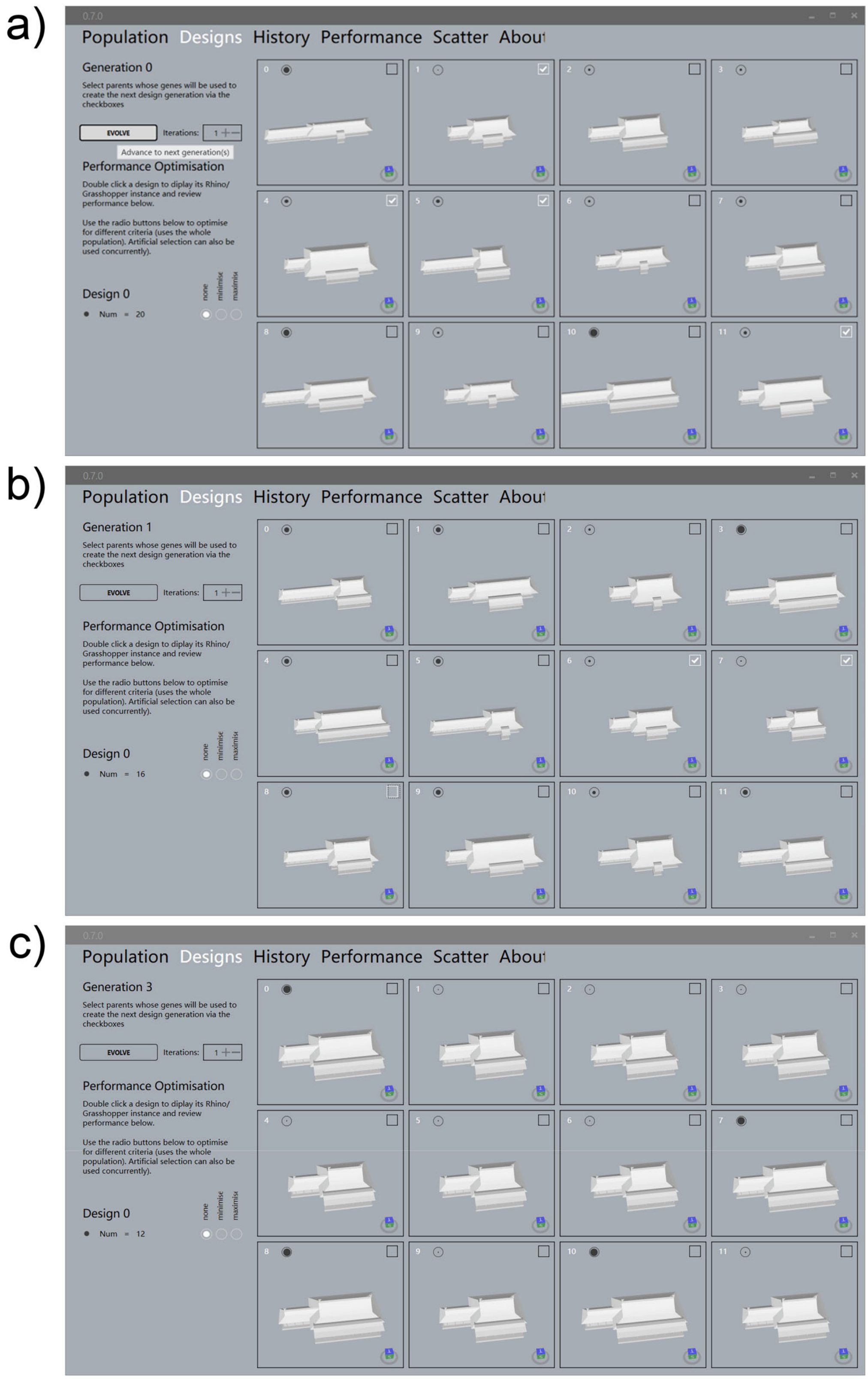


Fig. 6 | Interactive design through Biomorpher. This figure shows the multi-generation evolution using Biomorpher to compare random generated scenarios and select based on preference to approach the ideal solution. **a** Zero generation; **b** First generation of evolution - multiple scenarios comparison; **c** After multi-generation evolution - close to the ideal solution.

architectural massing typologies. This interdisciplinary tool not only enriches our understanding of Song Dynasty architecture, but also sheds light on future innovations in architectural conservation, education, and dissemination.

Data availability

The datasets used and analysed in the current study are available from the corresponding authors upon reasonable request.

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Author contributions

Yan Zhou conceived the research idea, collected the data, completed the modelling and data analysis, completed the data visualisation, and wrote the manuscript. Morun Zhang helped with the modelling and data visualisation. Luke Li* helped with the development of the research idea and supervision. Weixin Huang helped with the supervision.

Competing interests

The authors declare no competing interests.

Additional information

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