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Digital Twin for Xiegong's Architectural Archaeological Research: A Case Study of Xuanluo Hall, Sichuan, China

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Abstract: Xiegong is a unique element of Chinese historic buildings that could date the heritage dynasty. It is more complicated than the Dougong and represents a high level of artistic and structural achievement. Archaeological research on Xiegong is urgent due to the fast rate of erosion rate and the official record of only Dougong without Xiegong. With 3D survey technology, researchers can use 3D digital replicas to record and survey heritage buildings. However, the methodology of applying digital reproductions to facilitate archaeological research is unclear. A comprehensive approach to merging the digital twin into the chronology of forms was proposed based on a literature review of archaeological theory. This multi-methodological approach, including laser scanning, oblique photogrammetry, and BIM, was adopted to develop Xiegong's architectural archaeology dating research. Using Xuanluo Hall, Sichuan, China, as an example, the site study verified the approach to ensure consistency between 2D and 3D expressions with geometry and semantics. The results indicate that, on the one hand, the digital twin process can help archaeologists recognize historical information. On the other hand, the results of their discrimination can be effectively recorded and easily queried, avoiding the shortcomings of traditional methods of information loss and dispersion.

Keywords: BIM; historic building; digital twin; architectural archaeology; Xiegong; Dougong; photogrammetry; laser scanning

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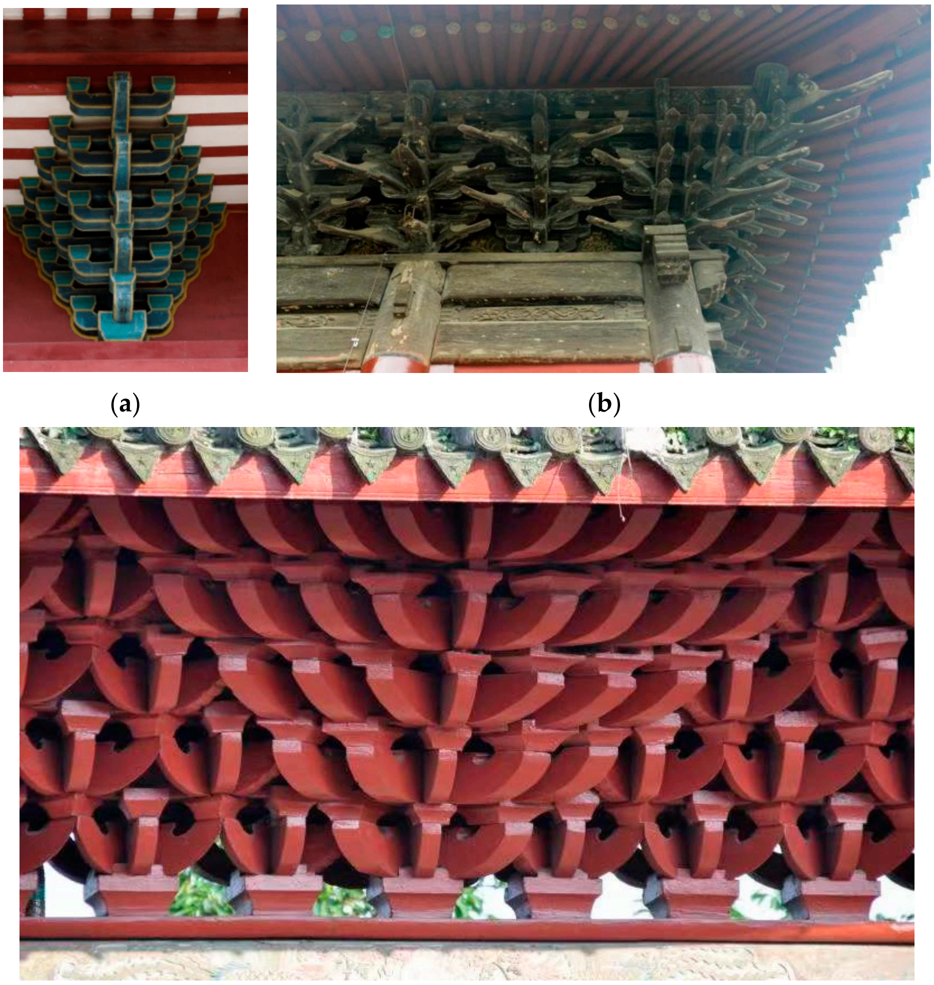
Citation: Tan, J.; Leng, J.; Zeng, X.; Feng, D.; Yu, P. Digital Twin for Xiegong's Architectural Archaeological Research: A Case Study of Xuanluo Hall, Sichuan, China. *Buildings* **2022**, *12*, 1053. https://doi.org/10.3390/buildings12071053

Academic Editors: S.A. Edalatpanah and Jurgita Antucheviciene

Received: 30 May 2022
Accepted: 13 July 2022
Published: 20 July 2022

1. Introduction

Xiegong is an outstanding representative of the development of Dougong [1], also known as Ruyi Dougong or Shanshi Dougong. It appeared in the Song Dynasty. Although it has not appeared on the official building record, the practice of Xiegong has developed a unique style throughout the Yuan Dynasty to the Qing. It demonstrates the strong vitality and creativity of folk culture [2]. The high aesthetic and technological achievement has attracted the attention of American scholar HARRER Alexandra [3]. It has different angles of the oblique components and richer and more complex changes than the official Dougong (Figure 1), sometimes connected into a mesh with the whole (Figure 1c). Many Xiegong heritage buildings in southwest China are well preserved, but the humid climate threatens the maintenance of the architectural remains. In archaeology, it is significant to record historical traces timely and effectively, while regular maintenance, such as routine maintenance and painting, erases historical information. So, it is best to survey Xiegong buildings as soon as possible.



(a) (b) (c)

Figure 1. Comparison between the official Dougong and the Xiegong: (**a**) Offical Dougong; (**b**) Xiegong from Pingwu Baoen Temple Wanfo Pavilion; (**c**) Xiegong from Yibin Zhenwu Mountain Archway.

Thanks to the State Administration of Cultural Heritage's execution of the "Compass Program—Value and Display of Ancient Chinese Inventions and Creations", the application of TLS (ground-based laser scanner) and UAV (unmanned aerial vehicle) photogrammetry in has accelerated heritage surveys. Since 2018, the Housing and Urban–Rural Development Committee has launched a national digital archive of historic buildings. The geometric data for the 3D reconstruction of heritage buildings are an essential part of digital conservation. The technology of scan-to-BIM has been used to include relevant information to support the conservation and management effectiveness of the archaeological site [4]. However, the process of converting these virtual models with information into active elements for the archaeological study is yet to be explored.

Digital twin technology, which has been widely applied to urban [5–7] and a few heritage applications [8], shows its application prospects. As a data acquisition technology in the digital twin, TLS and UAV-based oblique photogrammetry technologies have shown their unique potential to investigate the status quo of cultural heritage [9,10]. These surveying techniques do not require physical contact, so they are preferred for heritage mapping to avoid damaging heritage buildings. HBIM and scan-to-BIM technology, which has been adopted as a key technology in digital twin modeling [11], played an important role in reconstructing the 3D digital heritage model [4,12]. Digital twin combines the systematic application of various survey technical methods [13] and BIM-based semantics [14]. Some examples in the literature combine the above methods for heritage survey, but no articles use digital techniques for Xiegong archaeological research.

This research is a sub-topic of the southwest Xiegong research project, which aims to conduct an archaeological study on the multiple Xiegong buildings with rich historical and cultural value [15] in Southwest China and analyze their space–time evolution. According to the preliminary survey of the project, more than 30 Xiegong buildings built in the Song, Yuan, or Ming dynasties are distributed in Sichuan and Chongqing. The archaeological information is intricate, and the process of archaeological reasoning is often repeated. Manual processing of archaeological information data is prone to errors or omissions. Research requires more than just 3D models containing archaeological data. There is a greater need to digitize modern archaeological processes. That is, to take a step forward from scan-to-BIM modeling to propose a digital twin of the archaeological process.

The impact of decision making on heritage conservation projects has two aspects: identifying the historical and architectural value of the building and assessing its physical consistency [16]. Architectural archaeology is the scientific basis for evaluating history and architectural significance. Architectural archaeology needs to interpret the cultural importance of heritage buildings, but it is complicated and confusing. The latest archaeological research method recognized by the Chinese Archeology Professional Committee is shape chronology [17]. The heritage often preserves components from multiple periods, reflecting the centuries' traces of repairs and restorations. Shape chronology is based on the relationship between the time-sensitive components and age. It is essentially based on critical clues drawn from historical records related to physical heritage. When multiple historical clues and the Physical Heritage corroborate, a chain of evidence can lead to conclusions.

In this context, as modern architectural archaeologists tend to implement innovative techniques for 2D/3D documentation, the transition from heritage BIM models toward a digital twin process could be considered the next technological revolution in the archaeological analysis process. Therefore, this work employs heritage BIM and 3D reconstruction from point data in archaeological digital twin processes. In addition to methodological testing of the scan-to-BIM approach, this paper focuses on integrating digital twin into archaeological studies and heritage valuation. To verify the effectiveness of the digital twin framework for architectural archaeological research, we use the Xuan Luo Dian as a case study. However, due to the lack of archaeological information, the goal of this case study is to complete the first step of digital twin. The Xuanluo Hall, Sichuan, China, was digitally surveyed using TLS and UVA-based oblique photogrammetry techniques. With 3D reality modeling, archaeological analysis, and semantic-rich BIM model, the case research validates the first step of the digital twin process on Xiegong in Xuanluo Hall.

2. Related Works

2.1. Digital Heritage

Digital mapping technology provides more detailed geometric information about the heritage, including material, carving patterns, and cracks. Based on more detailed surveying and mapping results, research on the degradation states [18], deformation [19,20], and performance [21] of the heritage building is also increasingly being conducted. In particular, developing online heritage information platforms and digital archives has become a research hotspot, allowing experts (archaeology, archives, structural engineers, and restoration personnel) to share data [22]. Poux [23] recommended a point-cloud-based platform that employs point cloud segmentation as an interface model for linking data to avoid problems such as time-consuming geometric modeling and BIM data redundancy. Luis Javier Sanchez-Aparicio [24] proposed a panoramic platform based on Web-GIS, linking sensor data such as temperature and humidity monitoring. It can use digital heritage to query environmental data and display warnings of risky environments.

It is common to create visual interactive platforms for management and virtual tours, which demonstrate the effectiveness of cultural communication and explore the broad application of digital methods in the context of heritage conservation. Illsley states that a virtual model of Gothenburg in the seventeenth century was made to inform future heritage practices in the city [25]. Burkey used the qualitative studies of eight cultural heritage communities and a digital heritage initiative to build a new ecosystem for cultural heritage and corporate memory [26]. "Smart heritage" is developed using 3D models and augmented reality to study and communicate architectural and urban values [27]. Heritage documentation and dissemination activities, such as on-site observations, analysis, and intervention, can be interconnected in a digital environment, enabling multi-time and multi-dimensional management of the available information [28]. Digital technology offers the opportunity to show the past urban and architectural configuration to research and highlight the current historical and architectural importance.

2.2. BIM for Heritage Buildings

BIM has shown bright building archaeological application prospects [29]. The Digital Twin Theory lists the BIM model as architecture's preferred digital copy model due to its superior information integration advantages [30]. Semantic enrichment enhanced the quality and level of non-geometrical information on the 3D model [31]. BIM shows the capacity to integrate information by applying the CCIDOC CRM standard from an ontology's perspective and making semantic enrichment [32].

With the emergence of laser scan data integration in the BIM environment, some research has been focused on applying practical BIM methods to overcome the expression barriers of HBIM. Palomar [33] developed the BIM Legacy platform, a unified and synchronized online platform for heritage building information. The internal HBIM database is linked with traditional literature data to promote effective collaboration among different participants. Yang [34] pointed out that HBIM functions should be expanded by integrating other technologies and summarized the role of these technologies in heritage literature. There are two main scan-to-BIM modeling techniques: one is to use drawings and scan data for parametric modeling, and the other is 3D modelling of complex surfaces based on NURBS. NURBS represents the integration of surface and point cloud algorithms to improve the degree of automation [35]. Research on Chinese wooden architecture includes the method of automatic parametric modeling of bucket arches based on point clouds [36], the automatic creation of a column network system [37], and identifying roof decoration components to set up the model library [38].

The trend of BIM application in heritage building research combines digital twins. In the AEC-FM industry, as IoT development increases the interaction between the natural and virtual worlds, BIM and digital twin combine data collected by the IoT in the digital twin for disaster simulation to reduce disaster risk and improve management efficiency [39]. Similar research has also been extended to the field of heritage protection and heritage asset management. A digital twin framework for heritage protection is proposed, which is thoroughly combined with preventive protection theory and value analysis theory [40].

2.3. Digital Twin

Digital twins, which establishes interactions between the natural and virtual worlds, are becoming essential tools for the AEC community [41] to achieve industry 4.0 with IoT and deep learning [42]. In the future, digital twins are expected to provide new possibilities for networked physical systems through monitoring and simulation. The application of digital twin in smart city research trends is growing. Based on the relevant literature reviews regarding the use of the IoT in the built environment and analyses of current practices, Alshammari expanded BIM specifications to become IoT-compliant, enhancing standards to support cybersecurity [43]. Alizadehsalehi proposed an automated construction progress monitoring system that integrates BIM, various reality capture technologies, AR technologies for collaborative work to create, capture, generate, analyze, manage and visualize construction progress data, information, and reports [44].

Signs of application digital twin frameworks applied to the estate are also emerging. As argued by Angjeliu [45], digital twin applications in historical masonry buildings help assess the present structural conditions with high precision. Zhang [46] proposed an automatic ventilation system based on the IoT and a digital twin platform to optimize underground sites' relative humidity. Jouan [8] proposed the research framework for applying digital twin principles to support preventive conservation research. As they mentioned, HBIM models are used as a digital replica to provide data in the theoretical framework of preventive protection combined with sensors.

Most importantly, current research focuses on monitoring and simulation to help form maintenance management and intervention plans. However, few studies have focused on the value analysis of heritage. Ji-Soo Kang illustrates that the digital twin implementation can be divided into three levels. At level 1, the primary attributes of natural objects are reflected. At level 2, a digital replica can perform monitoring with the data from the real world by IoT. At level 3, advanced analyses and simulations can be achieved by machine learning [47]. In other words, level 2 and level 3 are studied a lot, while level 1 is studied less. On the contrary, level 1 is the most important because it is the foundation for heritage building maintenance, management, and restoration. The lack of research on the essential attributes and values of heritage buildings may lead to the risk of building heritage when implementing levels 2 and 3.

3. Study Site

According to the research on the main subject, more than 30 research objects are currently planned, mainly concentrated in southwest China, and their geographical distribution is shown in Figure 2. The Xuan Luo Dian is one of the most representative research objects. Built-in the Ming Dynasty (1596), it is a national cultural relic protection unit with an Octagonal pointed roof and a three-tiered eave. The hall was discovered when the Construction Society moved to Lizhuang Town, Yibin City, Sichuan Province, during the War of resistance against Japanese aggression. Lizhuang Town is located on the banks of the Yangtze River. Xuan Luo Hall is situated on a massive rock at the foot of Shiniu mountain, 2.5km south of Lizhuang, where Liang Sicheng, Lu Shen, and Luo Zhewen often went. Liang Sicheng commented on Xuanluo Hall: its excellent beam and column structure are pretty proud of the contemporary work.

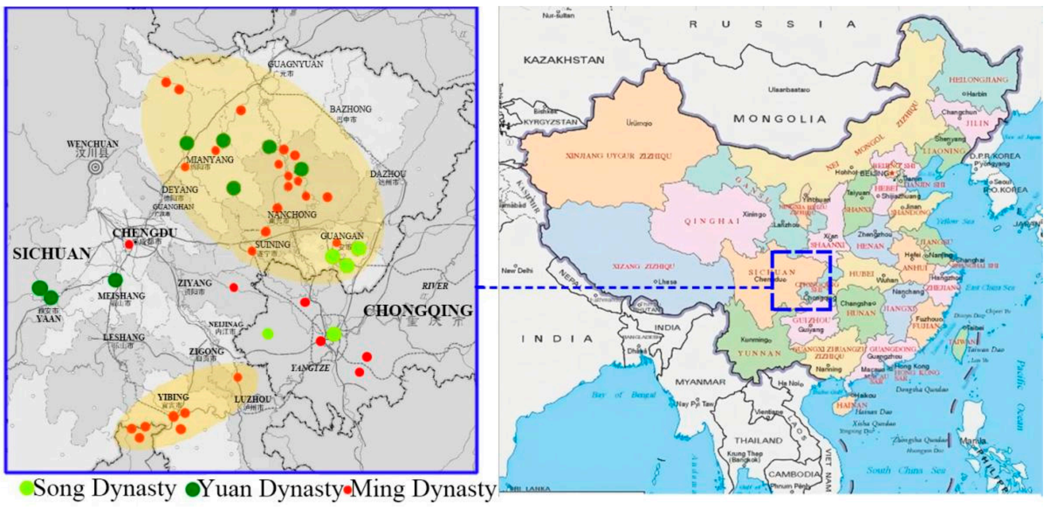


Figure 2. Distribution of Xiegong buildings in the Song, Yuan, and Ming Dynasties in Chongqing and Sichuan [15].

As the representative wood construction work in the late Ming Dynasty in southwest China, Xuanluo Hall's design is different from other temples because the octagonal caisson at the top appears to spiral upward, and a dragon head was placed in the middle of the caisson (Figure 3). The bracket sets in the first and second layers are separate, but at the top layer, they are connected to form the network surface. The same side of Xiegong is marked red in the picture from inside and outside (Figure 4a,b). Figure 4c is a detailed view of a bracket set. The element on the left side is equipped with Ruyi Dougong, and on the right side is the oblique wing. Such units are repeated alternately to form the rear tail of the Ruyi Dougong, and the oblique wing overlaps upward in a mesh shape and rotates to the right.

Figure 3. Study site: (**a**) Location; (**b**) The photos of Xuanluo Hall.

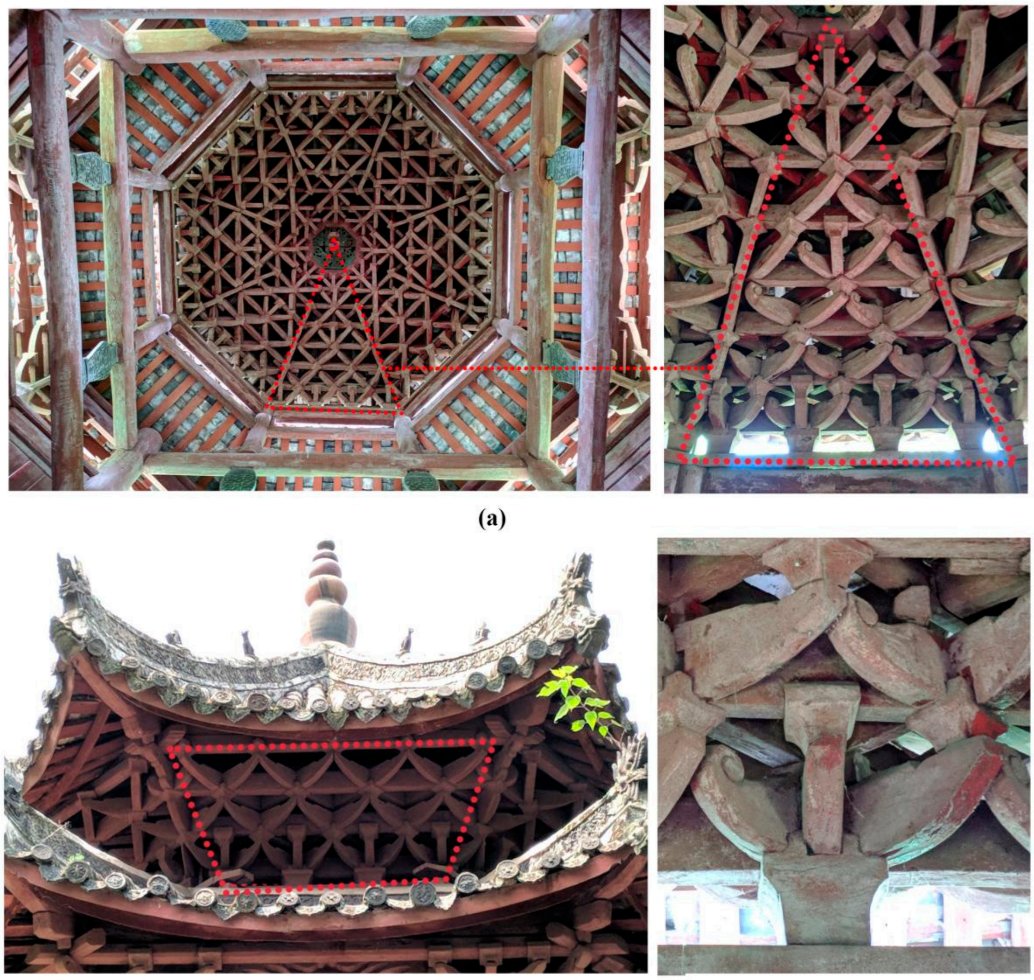


Figure 4. One side of Octagonal Xiegong on the third eave. (**a**) Xiegong on the third eave from inside and detail of one side; (**b**) Xiegong on the third eave from outside; (**c**) detailed of a bracket set.

4. Methods

4.1. Theory of Architectural Archaeology

The architectural archaeology study was carried out almost simultaneously with the founding of the Society for Research in Chinese Architecture in the 1930s. Unlike general archaeological objects, the object of architecture archaeology is that the building remains on the ground instead of under the ground. Therefore, it does not apply to the available method of stratigraphical archaeology. Xu [48] proposed a different approach called shape chronology. This method can scientifically and accurately judge the age rather than roughly judging the dynasty. Case studies [49] have been conducted to verify the rationality of the theory by specialists [15,50]. One of the most outstanding values of this theory is to determine the original structure because this is an essential basis for judging the rarity and significance of heritage. There are four steps to the study of shape chronology.

4.1.1. Surveying and Classification of Shape Features

The first step is to classify the age-sensitive components. Before that, you must survey enough well-preserved heritage buildings rich in historical records. According to previous studies, the age-sensitive part here usually refers to the Dougong bracket sets. It is not difficult to tell the age according to the shape feature of Dougong because the form of bracket sets changes quickly, and the characteristics of the same periods are consistent. Figure 5 shows the flows of this step, and the challenge of this step is that there are currently some references of official bracket dating but few are Xiegong. Primary data of cases take a lot of time to collect and analyze.

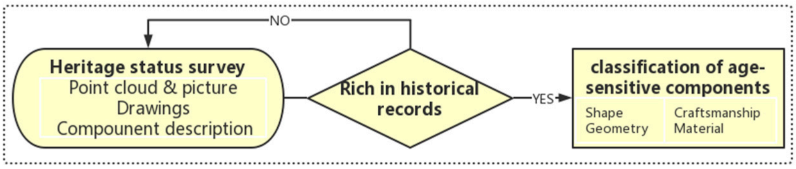


Figure 5. Survey and classification of shape features.

4.1.2. Identifying the Original Components and Original Design

Figure 6 shows the reasoning process of the original components. It is better to judge the original parts if the heritages have undergone few restorations and are richly documented. These records rely on county annals from different periods and are often incomplete. Cases from the same period and district could help. Archaeologists identify the replaced elements based on classification conclusions and then infer the original components and design from clues verified by historical documents. It is difficult to draw a definite conclusion due to insufficient evidence, so it is necessary to locate historical information from similar components in multiple cases in the same region.

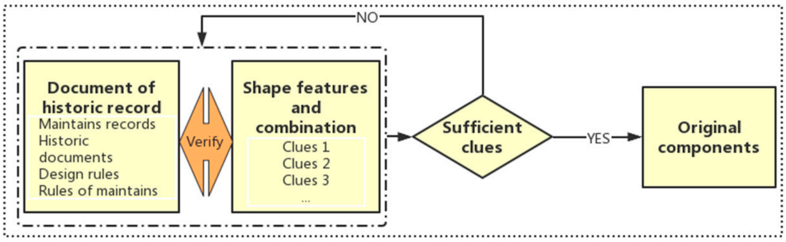


Figure 6. Identifying original components.

4.1.3. Compilation of Shape Chronology

The architectural heritage, the chronological extent of which has been determined, can be used as a ruler building in the same region. Figure 7 shows the flow chart of the shape chronology inference process. The original component in the ruler building is the ruler component, whose shape is the ruler shape. The authentic pieces in the ruler building agree with the age and can be used as a standard for dating. After collecting sufficient cases, the archeologist can determine the chronological interval of the ruler component and sort the chronological table of the region according to the chronological interval. Heritage buildings are complex, and their historical information is often incomplete or uncertain and associated with multiple spaces and times. Therefore, the shape chronology is long and needs repeated confirmation and adjustment. Any disturbance information may produce a series of linking errors, and more evidence chains formed by associating contemporaneous cases or historical data are needed to exclude disturbance information.

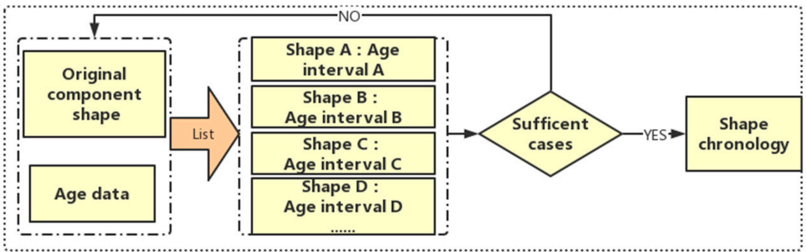


Figure 7. Compilation of shape chronology.

4.1.4. Dating of Single Buildings

According to the "Shape of original components simultaneity principle of the same building" (Figure 8) proposed by Xu [51] all the original components in the same building must exist at the same time. The initial construction period of the heritage building is the intersection of the actual component shape's age. The upper limit of the intersection is the upper limit of years in which the original structure could appears at the latest; the lower limit of the intersection is the lower limit of the years in which the original structure could disappear at the earliest. As Figure 9 shows, it can significantly shorten the period of a building's initial construction by analyzing the component shape or a combination of forms within a short period. It helps to improve dating accuracy and proves to be a more accurate shape chronology.

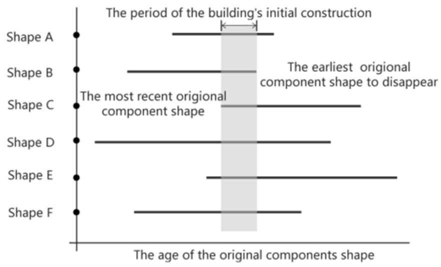


Figure 8. Schematic diagram of simultaneity principle of the same building [51].

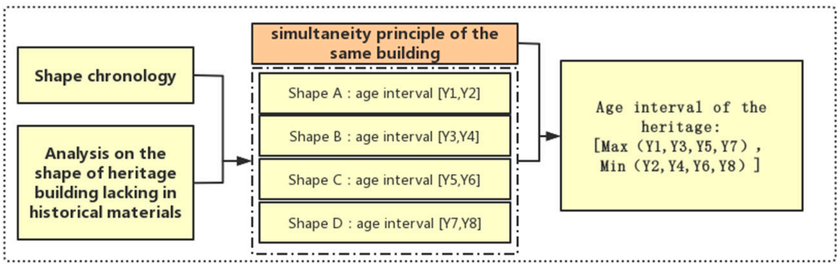


Figure 9. Single building dating.

4.1.5. Reference Indicators for Heritage Evaluation

The evaluation process of heritage value is complex, including tangible and intangible aspects. According to the cultural value model of Stephenson [52], it should objectively describe the heritage building value. The critical research of Fredheim and Khalaf believes [53] that value typology should remain open and change according to different time and space backgrounds. They suggest using "qualifiers of value" (authenticity, rarity, condition) to help define the heritage value. They proposed three crucial stages of evaluation. First, the assets to be evaluated are listed, then the reasons for their cultural value are revealed, and finally, the value of the identified elements is determined.

Therefore, this paper adopts some indicators as references for value evaluation, and Figure 10 shows the calculation process. These indicators are easily calculated based on the results of previous archaeological analyses. The number of original components divided by all members can indicate the remaining percentage of elements dating back to a specific stage in the existence of a building. The number of actual elements divided by similar pieces in other buildings can indicate rarity if the same type is documented in a shared database. It can feed the assessment of heritage sites' cultural significance by experts and avoid the eternal debate about the meaning of authenticity. The calculation method of indicators is not the focus of this paper; after all, this paper emphasizes calculating some necessary indicators through archaeological analysis data as a reference for value evaluation.

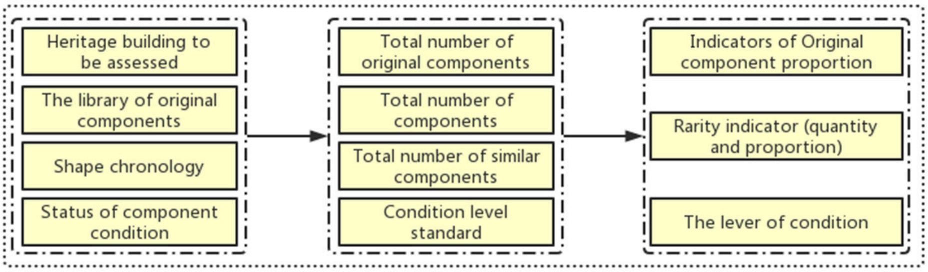


Figure 10. Reference indicators for heritage evaluation.

4.2. Digital Twin: A BIM-Based Comprehensive Method for the Archaeological Plan

In essence, this systematic method is based on Xu's shape chronology principle and quantitative method of cultural estimation. With the Digital Twin concept, a semantic-rich BIM model is integrated to support the study of shape chronology and provide specific quantitative analysis for cultural value evaluation. The process is combined with archaeological research and is divided into three steps, as shown in Figure 11. The first two steps are critical to ensure that the digital replica truly reflects the physical heritage. In this way, archaeologists can analyze details to obtain historical information. If the base data are insufficient, the first step must be repeated. In the second step, a parametric model is established in the BIM environment concerning point cloud data, and essential attributes are added according to archaeological information requirements. In the third step, the digital twin sets up the association between data and reason according to the applicable rules.

It is worth noting that the site study covers three steps of the method but does not complete all the work of the third step, which involves primitive component reasoning. It is used in the present experiment to determine whether this method should be used in subsequent case investigations. Xuan Luo Hall was surveyed in 2018 using a traditional survey method and then in 2021 using a digital survey method. Figure 12 summarizes the technique used to conduct this site study. A historical survey was carried out in 2018 to provide information about its history. The current state of the structure obtained from digital survey technology contains much more detailed information that can be used for BIM modeling and identifying archaeological features. The BIM model covers the point cloud to form a digital replica for archiving, visualization, and archaeological analysis.

4.2.1. Build a Digital Replica in a BIM Environment

Surveying includes both fieldwork and in-house work. In the fieldwork of Xuanluo Hall, Faro Laser Scanner Focus 350 is used for 3D scanning, with nine stations outside the heritage and 16 stations inside (Figure 13). Considering that more internal beams and columns shelter each other, the layout of the internal scanning points is dense. Therefore, internal data can be accurate and complete, except for the top surface of the components, which it cannot obtain due to the height limitation of the scanner. However, external data on some roofs are incomplete due to space limitations. Mavic 2 Pro DJI uses DJI UAV to preset the circular path directly towards the center of the ring for photography. Figure 14 shows the flight path, camera location, and control points. Data obtained by the UAV have a complete roof, but data under the eaves are incomplete because the surrounding trees are higher than the roof.

In-house work registers the point cloud from LAS and makes a dense point cloud model through photography. The point cloud is converted to the RCP format as a reference to import the BIM environment. Figure 15 shows the point cloud imported into Revit and the view with the profile box. Then, the point clouds are aligned with the control points. According to the semi-automatic modeling method [28,54] or parameterized modeling method [55], Xiegong component libraries are modeled. With the help of parameterized libraries and survey data, it was efficient to build the Xuanluo Hall BIM model. Therefore, the BIM model with accurate size and the point cloud model with complete information constitute the digital replica. The point cloud link to the BIM environment can compensate for the BIM model of the missing environment, surface texture, material details, and carved patterns.

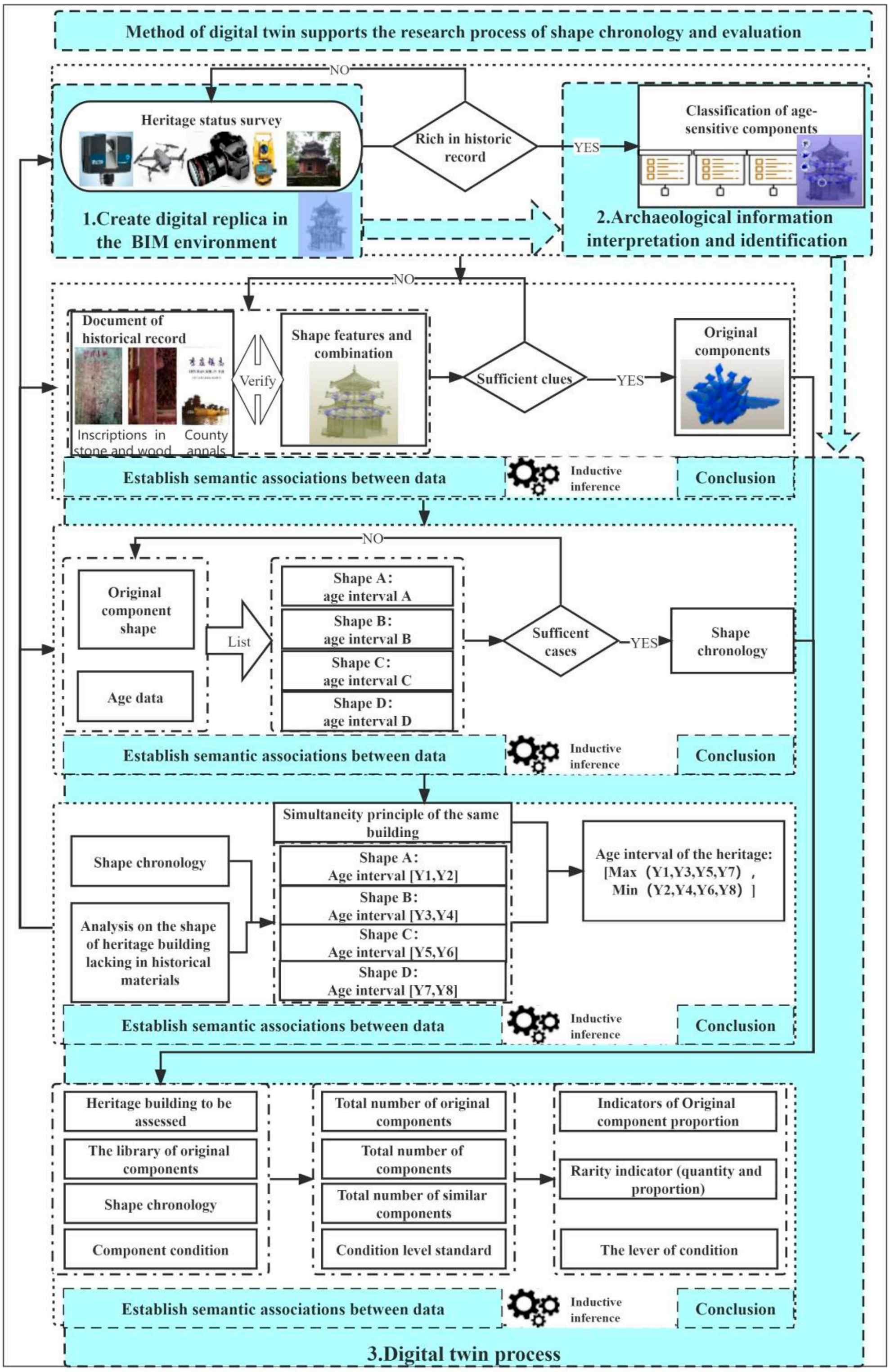


Figure 11. Three steps in the digital twin method to support archaeological research.

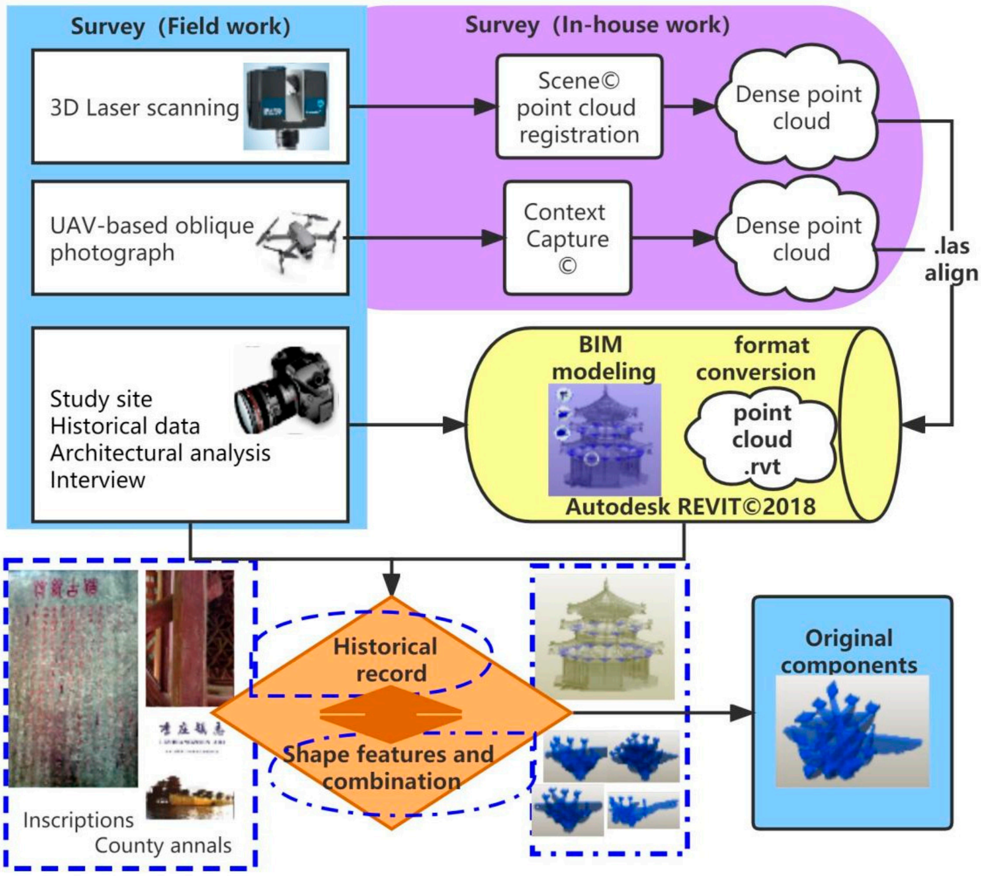


Figure 12. Site study methodology flow.

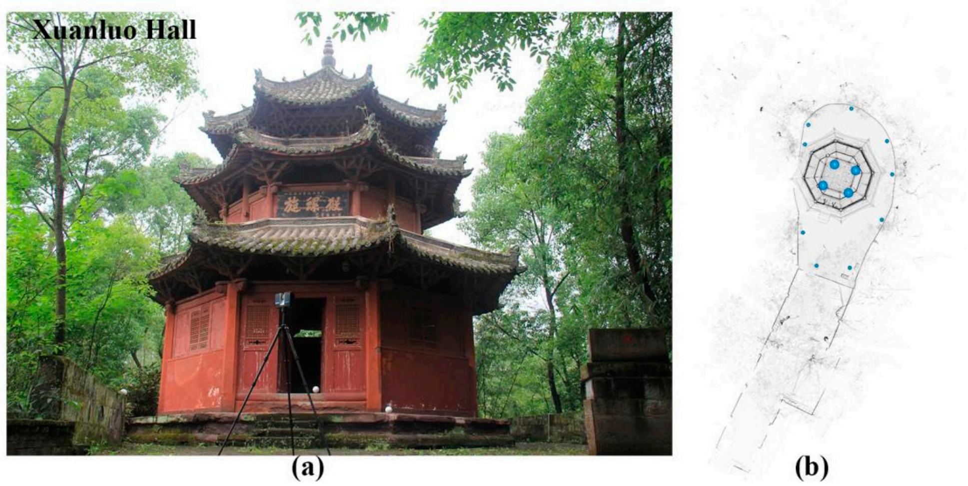


Figure 13. Xuanluo Hall scanning. (**a**) Faro Laser Scanner used in this work; (**b**) distribution of stations.

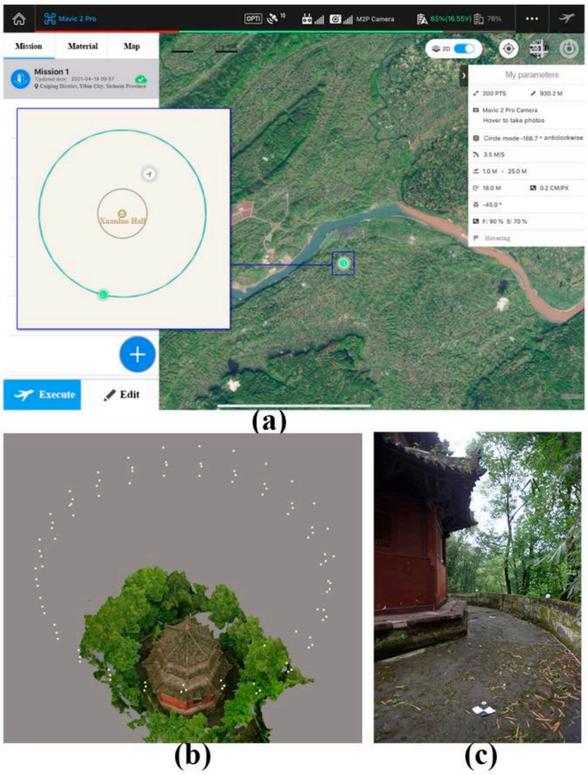
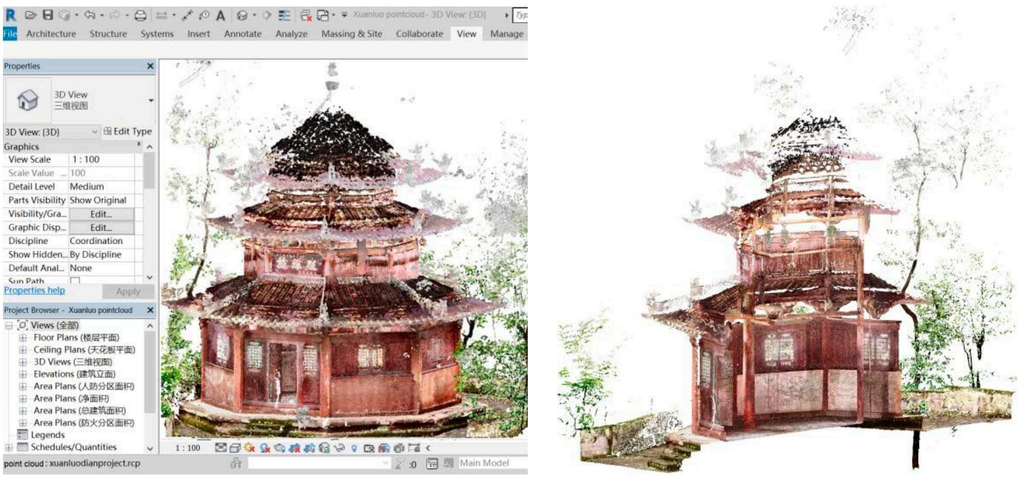


Figure 14. (**a**) Flight path arrangement with DJI GS pro; (**b**) Camera location; (**c**) Target of the control point.



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

Figure 15. Point cloud in BIM: (**a**) Point cloud in Revit; (**b**) View with the profile box.

4.2.2. Archaeological Data Interpretation and Identification

Archaeological information is varied and complex and needs to be interpreted by people from different professional backgrounds. Architectural archaeologists can make specialized interpretations of building components because of their personnel professionalism. Once the clues are found, they must be identified in the BIM environment. It is emphasized that the properties of archaeological data differ from the family library's character. It is easier to confuse with the modeling named here. Most modelers do not know the name of the heritage building components. For example, details in Dougong are not unified, with different names in different dynasties. So, modeling researchers named the elements according to the modeling efficiency, a professional component name, according to archaeological needs for semantic annotation. The same component uses a family database to improve modeling efficiency. However, the archaeological information about each element in the heritage is different and needs to be identified one by one.

Semantic classification is still an open research field. Strict classification will conflict with the uniqueness of historical buildings and the different analysis methods used by multidisciplinary personnel in design research and protection, so there is no standard way of working [56]. A common standard language is needed for data compilation, evaluation, creation, transmission, and storage to facilitate communication among all personnel involved in conservation. Therefore, it is necessary to establish a semantic definition standard to support the archaeological research, and then it can return the research results to the database as open access data. The method adopted in this case is to add semantic labels in the BIM environment. As only the semantics are added to the bracket set part, it is enough to use the IFC format for data interoperation. Figure 16 shows the attribute interface after adding information for one of the bracket sets. Six description tags are defined according to archaeological requirements and are associated with unique identifiers for the easy query. In addition, links to images and panoramas have been added for ease of understanding, positioning, and avoiding confusion.

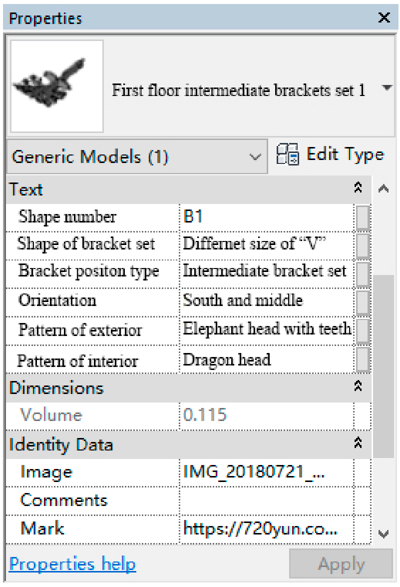


Figure 16. Archaeological data interpretation and identification.

4.2.3. Digital Twin Process to Support Architecture Archaeology

The digital twin process extracts information from the actual scene model for archaeological reasoning, and the reasoning results are returned to the BIM database (Figure 17). Generally, exploring the original design or component first needs to be hypothesized and then the matching clues are found to prove the hypothesis. However, archaeological data are not immediately available and are often inconclusive. When processing new clues in the digital twin, data related to previous inferences and reasoning rules can be easily invoked and updated from different taxonomic and attribute perspectives. Therefore, the convenience of data recording and extraction is essential, and the benefits of HBIM integration are fully realized here.

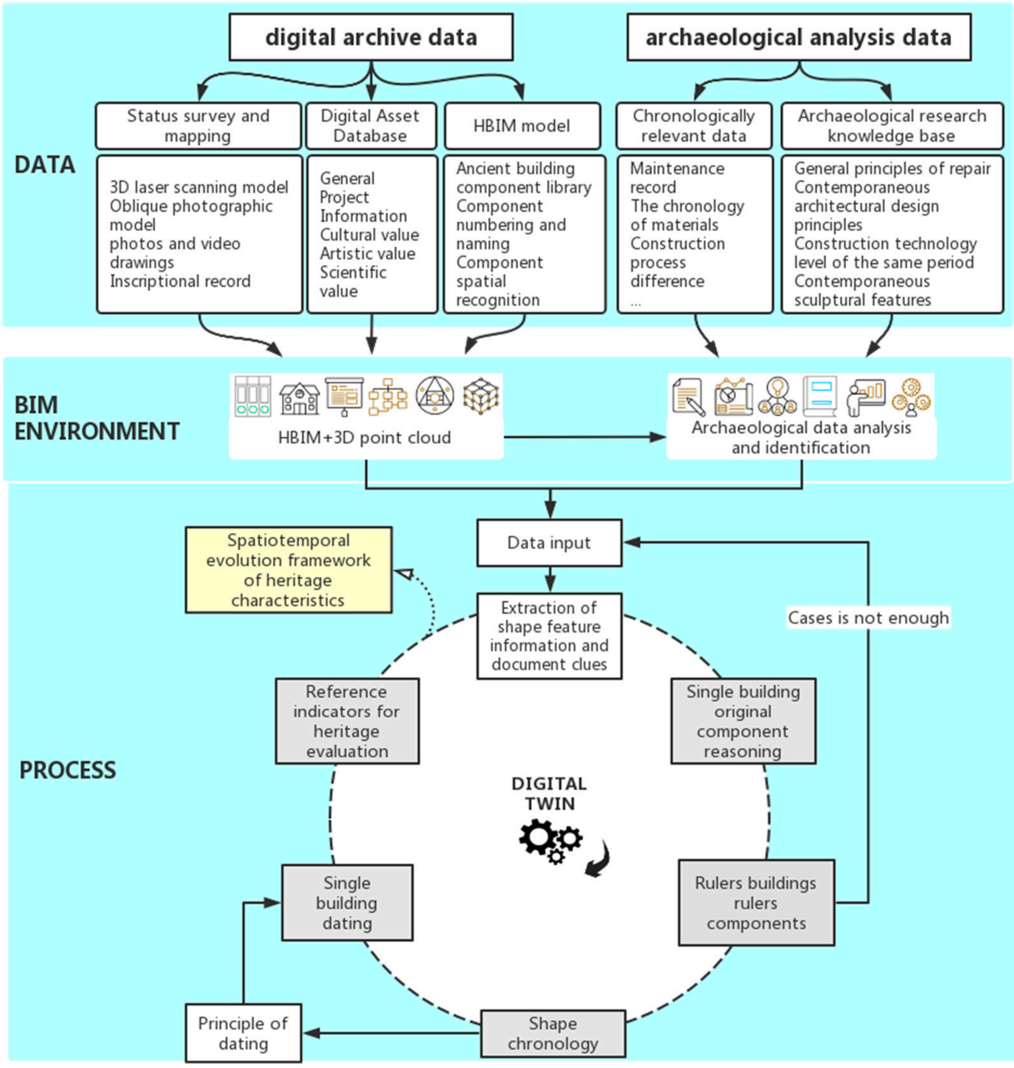


Figure 17. The Digital Twin process supports archaeological analysis.

4.3. Data Management in the BIM Environment

Combining the HBIM and heritage point clouds as a digital replica supports the digital twin of architectural archaeology. Professionals should assess and identify valuable survey data for archaeological reasoning to create archaeological evidence. Relationships between archaeological evidence and models based on available historical data are essential. It is possible to conclude when many indices point to an assumption simultaneously. This section will discuss the data management in the digital twin process of archaeology, which has three main parts: data input, data comparison in the BIM environment, and data output. Data input is clear at a glance in Figure 17. Data comparison in the BIM environment is present as a digital twin process, and the gray box is the data output. The yellow box is the long-term goal of data output.

Data input compiles the initially collected data, including digital archive and archaeological analysis. Digital archives and historical data, often reflecting value, can be linked to the project as an external database. It should connect detailed photographs such as engravings to the relevant component in the model, which can avoid the trouble of flipping through different photo folders in archaeological identification. However, according to the requirement, panoramic images (Figure 18) must be linked to the HBIM subject or as independent external data. Therefore, the digital archive data in the BIM environment are mainly expressed through the point cloud model and the property link of the HBIM model.

Figure 18. Panoramic images in Xuanluo Hall.

In a BIM environment, data must be compared according to archaeological needs. The key lies in the correct compilation by the archaeologist, which connects the interpretation and model of many historical buildings to form the interaction between physical heritage and its history. Hypotheses will be put forward in archaeology, and it will examine various relevant clues to confirm them. The verified data become evidence of the following theory and reasoning.

Visual output is an essential benefit of the digital twin process. From an archaeological point of view, it can analyze ruler building and ruler components first, then a continuous update of the shape chronology. It is an essential reference for dating other buildings. In addition, it can obtain the quantitative results of valuable consideration and even the framework of the structural evolution of a region.

5. Result

5.1. The Digital Replica of the Xuanluo Hall

The point cloud data consist of roof data from UAV-based oblique photographs and primary structure data from LAS. Both LAS and oblique photogrammetry can only obtain part of the data because the site is small and the trees around it are taller than the building. It is necessary to combine the two data to make the data as complete as possible. Previously, oblique photogrammetry usually produced models only for visual observation. The point cloud makes the mesh more reliable and precise with software development and algorithms. The photogrammetry model is converted into the point cloud format and imported into the BIM environment. The LAS point cloud in the BIM environment is aligned with the oblique photography model by control points to form the complete point cloud of the heritage building (Figure 19).

Although the scan-to-BIM method GOG9-10 [56] has been studied through the direct transformation of NURB, it is complex and time-consuming, and it is not suitable for the shape and structure study of combined Xiegong. In addition, the pattern, engraving, and other information can be linked by character, so the traditional GOG1-8 method [35] is adopted to create the model of HBIM, and the reusable component library is made based on constructive knowledge of Xiegong.

Just as in the operation and management phase of the building, the need for model precision is not high, but the need for information is urgent. The same is true of architectural archaeology. From the cost perspective, even the semi-automatic digital twin method based on the drawings can meet the needs [54]. Therefore, the HBIM model can use a low LOD but high LOI model, generally LOD200-300. It must be noted that the information input in the high-information model here is not completed at once. Maybe there is only basic geometric information at first. The relevant information is gradually added with archaeologists' analysis and clue needs. Data are updated as new clues are discovered to investigate new cases. Therefore, it is a gradual improvement process.

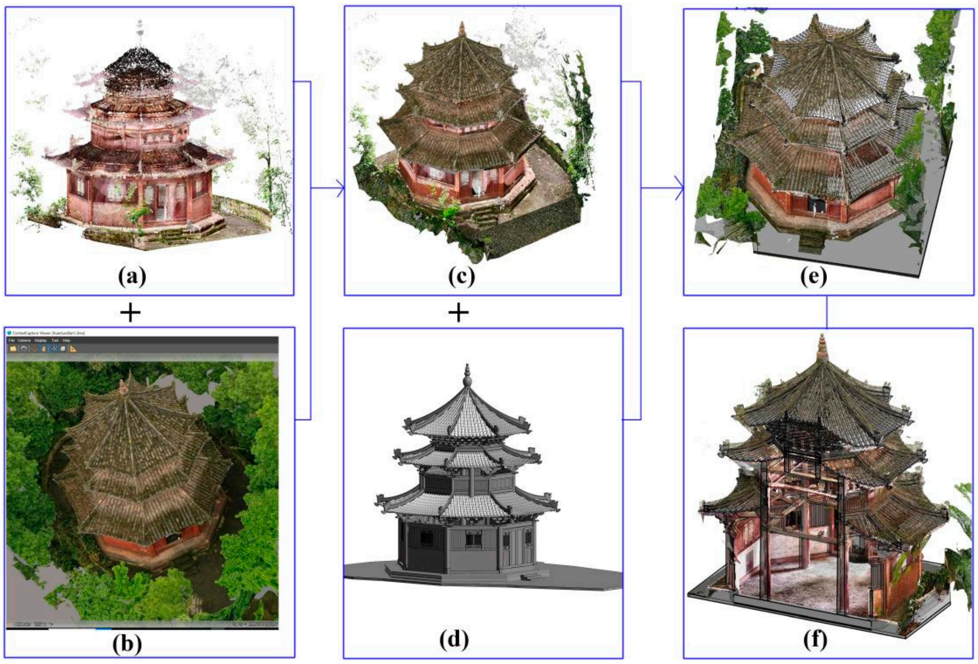


Figure 19. The Digital Twin modeling progress: (**a**) Point cloud model from LAS with an incomplete roof. (**b**) The model with an insufficient structure below the eaves from photogrammetry. (**c**) Complete point cloud of the Xuanluo Hall. (**d**) BIM model of Xuanluo Hall. (**e**) Point cloud with BIM model. (**f**) The section of point cloud with BIM model.

5.2. Archaeological Data within the Digital Twin

Critical data for archaeological analysis are geometry data and semantic information. All components of the Xuanluo Hall are reconstructed faithfully in BIM. Still, there are only models of Xiegong on the first and second floors with rich semantics because archaeological analysis of the third floor has not yet been conducted. Characteristics data from archaeological investigation of the two floors of Xiegong are associated with the corresponding element model to create a semantic-rich BIM. The component list of archaeological identification types can be automatically obtained within the BIM environment. All characteristics of Xiegong are evident at a glance from the schedule (Figure 20). The data transfer between the archaeologist and the BIM builder in the digital twin process is performed through the .xlsx format and the IFC standard. Using traditional methods to find the information about interior projections of the second perpendicular bracket arm requires turning over many drawings to obtain a single pattern, detailed illustration, detail size, and the spatial distribution of various designs. With the digital twin process, click on the bracket set model to select the semantic information you want to display and you obtain the spatial distribution of that feature. Figure 21 shows the spatial distribution according to the five patterns of interior projections of the second perpendicular bracket-arm.

Schedule of XieGong Shape and Pattern

Floor	Shape number	Shape of bracket set	Image	Bracket position type	Orientation	Family name	Image of exterior projections of second perpendicular	Pattern of exterior projections of second perpendicular bracket-arm	Image of interior projections of the second perpendicular bracket-arm	Pattern of interior projections of the second perpendicular bracket-arm
2	Z1	Differnet size of "V"		Corner bracket set	South and right	Second floor corner bracket set 1		Elephant head with teeth		Maye cloud
2	Z2	Differnet size of "V"		Corner bracket set	South and left	Second floor corner bracket set 2		Simplified elephant head		Maye cloud
2	Z2	Differnet size of "V"		Corner bracket set	Northwest	Second floor corner bracket set 3.1		Simplified elephant head		Maye cloud
2	Z2	Differnet size of "V"		Corner bracket set	North and left	Second floor corner bracket set 3		Elephant head with teeth		Cloud grass 3
2	Z2	Differnet size of "V"		Corner bracket set	North and right	Second floor corner bracket set 3		Elephant head with teeth		Cloud grass 3
2	Z2	Differnet size of "V"		Corner bracket set	Southeast	Second floor corner bracket set 2		Simplified elephant head		Maye cloud
2	Z2	Differnet size of "V"		Corner bracket set	Northeast	Second floor corner bracket set 2.1		Elephant head with teeth		Cloud grass 3
2	Z1	Same size of three "V"		Corner bracket set	Southwest	Second floor corner bracket set 1		Elephant head with teeth		Maye cloud
1	B1	Differnet size of "V"		Intermediate bracket set	South and middle	First floor intermediate bracket set 1		Elephant head with teeth		Dragon head
1	B2	Same size of three "V"		Intermediate bracket set	Southwest and middle	First floor intermediate bracket set 2		Simplified elephant head		Cloud grass 2
1	B2	Same size of three "V"		Intermediate bracket set	Northwest and middle	First floor intermediate bracket set 2		Simplified elephant head		Cloud grass 2
1	B2	Same size of three "V"		Intermediate bracket set	Southeast and middle	First floor intermediate bracket set 2		Simplified elephant head		Cloud grass 2
1	B2	Same size of three "V"		Intermediate bracket set	Northeast and middle	First floor intermediate bracket set 2		Simplified elephant head		Cloud grass 2
1	Z2	Same size of three "V"		Corner bracket set	Southwest and corner	First floor corner bracket set 2		Simplified elephant head		Maye cloud
1	Z2	Differnet size of "V"		Corner bracket set	Southeast and corner	First floor corner bracket set 2		Simplified elephant head		Maye cloud
1	B2	Same size of three "V"		Intermediate bracket set	North and middle	First floor intermediate bracket set C3		Simplified elephant head		Cloud grass 2
1	B2	Same size of three "V"		Intermediate bracket set	West and middle	First floor intermediate bracket set C2		Simplified elephant head		Maye cloud
1	B2	Same size of three "V"		Intermediate bracket set	East and middle	First floor intermediate bracket set C2		Simplified elephant head		Maye cloud
1	Z2	Differnet size of "V"		Corner bracket set	North and left	First floor corner bracket set 2D2		Elephant head with teeth		Cloud grass 2
1	Z2	Differnet size of "V"		Corner bracket set	North and right	First floor corner bracket set 2		Simplified elephant head		Maye cloud
1	Z2	Same size of three "V"		Corner bracket set	Northwest and corner	First floor corner bracket set 2D2		Elephant head with teeth		Cloud grass 2
1	Z2	Differnet size of "V"		Corner bracket set	Northeast and corner	First floor corner bracket set 2D2		Elephant head with teeth		Cloud grass 2
1	Z1	Same size of three "V"		Corner bracket set	South and right	First floor corner bracket set 1		Dragon head		Cloud grass 1
1	Z1	Same size of three "V"		Corner bracket set	South and left	First floor corner bracket set 1		Dragon head		Cloud grass 1

Figure 20. Schedule of Xiegong shape and pattern.

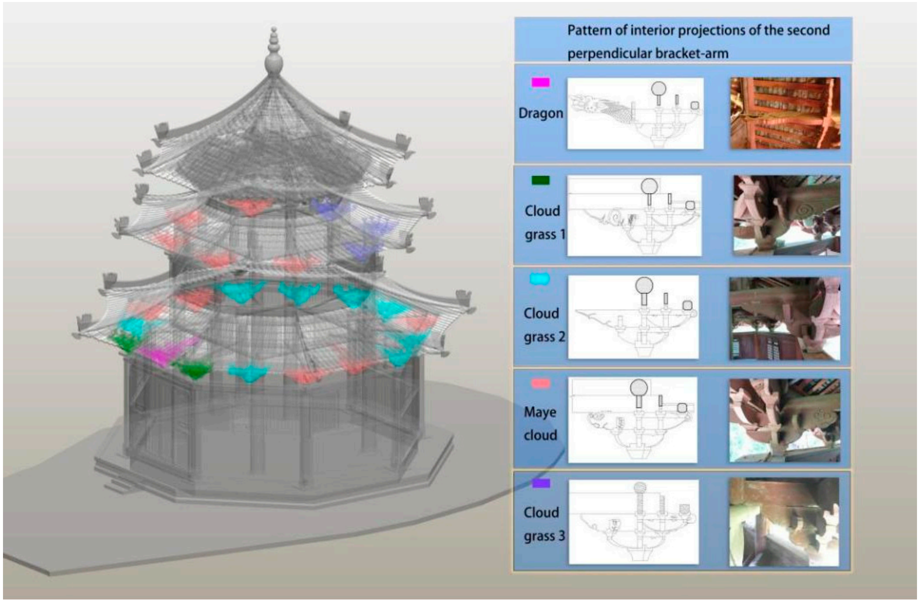


Figure 21. The spatial distribution of the pattern of interior projections of the second perpendicular bracket-arm.

5.3. Presentation of Archaeological Information for Reasoning

Reasoning needs multiple clues to prove one another. Here, based on the shape of the bracket set and pattern (Figure 22) of exterior projections of the second perpendicular bracket-arm (Figure 23) and the historical records and design rules, we concluded that Xiegong on the facade elevation of the second floor does not conform to the original design. Archaeological analysis has been omitted, as this article deals with digitization. Compared with the previous method, the digital twin method is more visual and makes it easier to find relevant clues.

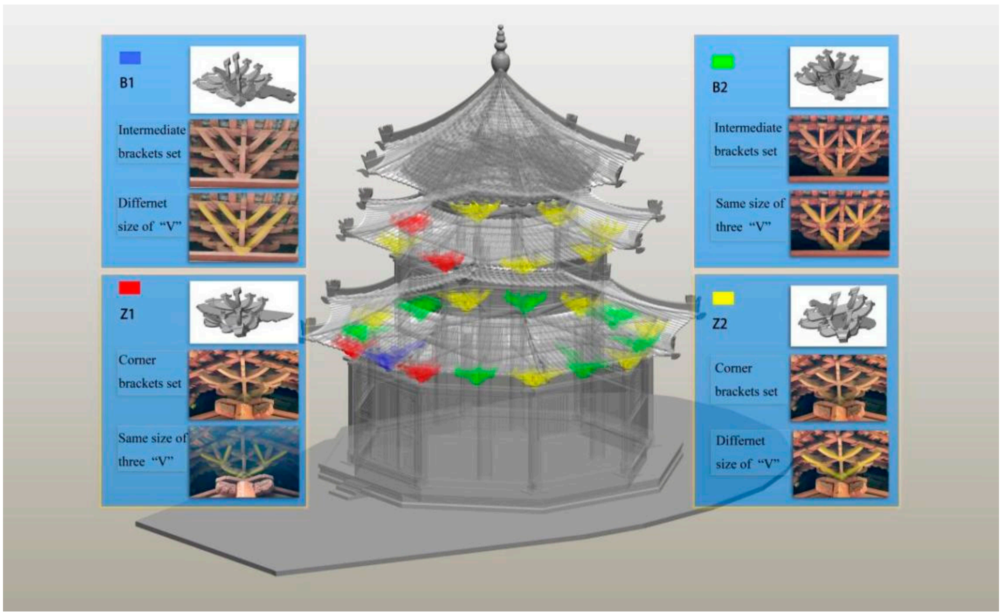


Figure 22. The shape of the bucket set.

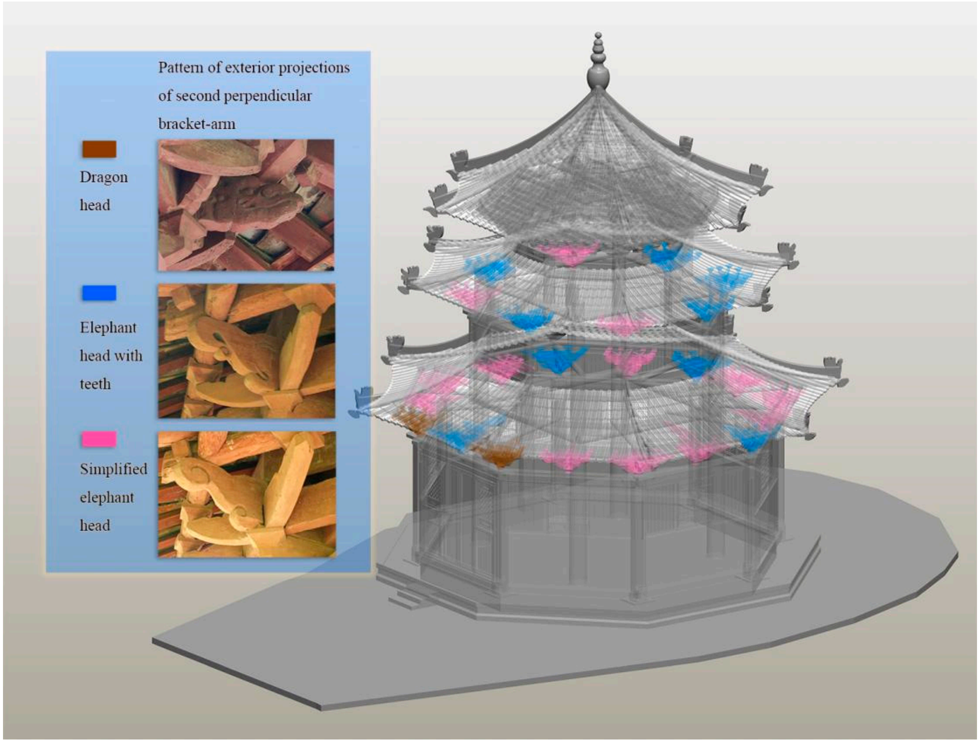


Figure 23. The pattern of exterior projections of the second perpendicular bracket arm.

6. Discussion

This method emphasizes the digital twin process, which connects the physical components of the heritage to the relevant data of architectural archaeological research. A visual database associated with the heritage components and environment is created to facilitate the query and analysis of research data. The database is dynamically growing with the analysis of more study cases. The specific archaeological analysis methods and evaluation indices of cultural relics in the research framework are not the focus of this paper, so these methods might not be very comprehensive. For example, the reference indicators in Section 4.1.5 for assessing the importance of buildings are incomplete. There are too many factors to evaluate heritage value, and specific analysis methods need to be determined according to the characteristics of the case.

The digital twin framework still has some challenges in establishing cases' semantic relationships between data and reasoning because architectural archaeologists are not good at BIM. Current research shows that developing and using the platform can improve staff participation and usability in various areas [33]. However, significant differences in architectural archaeological research cases make it difficult to set up a suitable data type and data structure at first. Therefore, instead of building a platform, we have adopted the archaeologists' approach of working closely with BIM personnel. It is proposed to establish a platform after completing several case studies and forming a comparatively fixed model, which is more conducive to cultural transmission and the preservation of heritage buildings.

In the case study, TLS and real scene models complement each other in the absence of data, but there is still incomplete data, which need to be completed in the future. In addition, all the components are modeled separately by the parametric method, but it is found that it is not necessary to model them all. Because most of the current information requirements for architectural archaeological dating concentrate on the various components of the Xiegong, it is essential to model the Xiegong's components in a parametric way to facilitate their association with external data. However, there are not many data requirements for other parts, so simplifying the modeling or even not modeling according to the follow-up research requirements may be a method to improve efficiency.

Another problem worth noting is that the scale of this case is not large, which can be achieved by importing point cloud into Revit software. However, when the amount of point cloud data is too large, problems will need to be carefully addressed in the future.

7. Conclusions and Future Work

In conclusion, this study shows the digital twin attempt to apply digital technology's development results to architectural archaeology research, mainly realizing integrating heritage status information and age information in the BIM environment. On the one hand, combining the point cloud model, oblique photography model, panorama, and detailed photos in the BIM environment promotes architectural archaeologists' identification of archaeological clues in an intuitive and friendly working environment. On the other hand, annotating semantic information of BIM for classifying and querying complex archaeological types as an essential part of the digital twin undoubtedly improves interoperability. The data structure in the BIM environment helps organize and represent geometric, spatial, and archaeological identification categories and chronological features of heritage.

Unlike traditional AEC applications that use IoT to connect the real and virtual worlds, the digital twins here use archaeologists' interpretation of heritage to connect the artifact's history and current status. The study highlights the digital twin for archaeological reasoning with a semantic-rich BIM model combined with point cloud. The scan-to-BIM approach is adopted, but it is also extended in combination with architectural archaeological dating studies. Compared to traditional approaches to architectural archaeology, the critical interest of this method is that it can competently deal with various uncertain clues in archaeological research and connect them with corresponding components. The digital twin process of archaeological research makes it easy to visually query the information and update all relevant data easily when old clues are replaced with new ones. Thus, it is possible to reduce the time to find data from complex drawings, prevent important clues from being lost, and map critical archaeological clues in the 3D environment.

Although the case study did not complete the digital twin process for heritage identification, subsequent case studies will continue to improve this approach. However, from the perspective of the method's contribution to archaeological research, it can draw some interesting conclusions:

- Currently, there is no systematic method based on the principle of Xu's shape chronology and a quantitative method of cultural estimation. This method applies not only to the archaeological dating of the Xiegong heritage but also to the official Dougong heritage.
- The data collected by 3D mapping technology are sufficient and avoid the loss of information caused by traditional information recording methods such as CAD drawing. It also provides reliable reference indices for cultural relic value evaluation.
- A 3D model that faithfully records the status and details of the heritage can be viewed in the BIM environment, which solves the problem of the archaeologist who cannot visit the site.
- The BIM model provides a medium for information storage for the process and results of architectural archaeological identification and analysis. It can be stored in the BIM environment or linked to an external database, providing archaeologists with various query methods.
- The digital twin process can better deal with the uncertainty of archaeological data. When new data are added to the BIM environment, it can update the related data synchronously to avoid errors caused by outdated information.

This study represents the first achievement of the whole project. The next step is to survey more cases, form an archaeological chronological database, and automate the dating of individual buildings. We will carry out work from the following aspects:

- There is currently a method to combine point cloud and photographic models into one model, which maintains accuracy and reflects reality. This method is ready to be adopted in the following case, but it may also meet the challenge of occlusion of the surrounding environment.

- Programs will be written according to the general steps and possible situations of Xiegong archaeological research in the future to improve the automation of the process.
- A data model will be developed for the data management of archaeological temporal evolution information. A prototype data structure for indicators related to heritage importance will be developed. In addition, interoperability issues need to be further studied.
- Building a platform and database for architectural archaeological research is the ultimate goal. A multi-user mode to provide a platform for data support, discussion, and exchange for different archaeological researchers may be a future research direction.

Author Contributions: Conceptualization, J.T., J.L. and X.Z.; methodology, J.T.; software, J.T.; validation, J.T. and J.L.; formal analysis, J.T.; investigation, J.T., D.F. and J.L.; resources, J.L. and X.Z.; data curation, P.Y.; writing—original draft preparation, J.T.; writing—review and editing, J.T.; visualization, J.T.; supervision, D.F.; project administration, X.Z.; funding acquisition, J.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation Youth Fund of China (51708051) "Study on development and evolution of Xiegong in Southwest China".

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: Thanks to Sichuan provincial cultural heritage administration for site support. The authors would also like to thank the survey group in 2018 for detailed drawings and Xin Zhou, Xiangnan Fan, Shiyi Chen, Yunyi Yang, Guoli Luo, Yuetian Li, and Ruiyang Wang for technical support.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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