# An Integrated HBIM-VR Framework Design for Chinese Classical Architecture Heritage Digital conservation and interpretation - A case study of Yangxin Hall in the Forbidden City

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**Abstract**

Traditional Chinese classical architecture, a crucial part of China's architectural heritage, has unique artistic and historical value. Its protection is increasingly recognized, but relying on timber structure, it faces threats from natural forces and human activity, making physical preservation fragile. A key conservation challenge is faithfully documenting architectural heritage throughout its lifecycle and overcoming barriers to audience engagement for sustainable value transmission. Digital technologies have enhanced heritage conservation efficiency. Heritage Building Information Modelling (HBIM) generates comprehensive datasets for sustainable management, while virtual reality (VR) offers immersive public interpretation. WebVR, a VR application, enables accessible online heritage experiences via web platforms. Integrating HBIM and VR shows potential: HBIM provides foundational data for VR, and WebVR expands accessibility on portable devices. Focusing on Yangxin Hall in the Forbidden City, this study develops an HBIM-VR-WebVR framework for heritage information access, management, and transmission across conservation phases. User experience surveys validate the framework, which supports heritage conservation and public engagement, offering reference for similar projects.

## 1. Introduction

Architectural heritage, as a primary type of cultural heritage, highly reflects various aspects of a society and its historical development (Dümcke and Gnedovsky, 2013) It influences people's cultural perception. Ancient Chinese architecture is dominated by timber-frame structures, which have created various floor plans and appearances compatible with this structure, forming a unique style (Liu, 1984). Chinese traditional official architecture, as a typical representative of ancient Chinese architecture, is also an important component of China's architectural heritage. Architectural heritage is an irreplaceable precious resource in the progress of civilization and an important treasure trove of each nation's historical heritage. As a vital part of sustainable development, architectural heritage holds profound cultural, economic, and scientific significance (Misirlisoy and Günçe, 2016).

To be listed on the UNESCO World Heritage List (WHL), heritage must meet the criteria of authenticity and integrity to demonstrate its Outstanding Universal Value (OUV) (Alberts and Hazen, 2010), reflecting that the value of architectural heritage relies on integrity and authenticity.

However, numerous factors such as environmental erosion, climate change, and human activities continuously threaten the survival of architectural heritage. The remoteness and dispersion of many heritage sites objectively lead to insufficient public accessibility. Additionally, heritage buildings may require closure for restoration or temporary closure to reduce interference, affecting their display and value communication to the public. Therefore, the challenge in heritage protection is to transcend the inevitable physical changes of architectural heritage in the real world, faithfully and completely record, monitor, and manage its information throughout its survival cycle and protection process, and continuously convey its value to the public.

The application of digital technologies in the heritage field has significantly improved the efficiency and quality of heritage protection, providing new solutions. A popular method for digitizing the richness of cultural heritage is Historic Building Information Modelling (HBIM), which comprehensively uses various BIM software to capture existing information and convert it into digital formats. This results in a complete 3D model including detailed information about construction methods and material compositions behind the object surfaces. HBIM automatically generates comprehensive engineering drawings for the protection of historical structures and environments, including 3D documents, orthographic projections, sections, details, and schedules (Dore and Murphy, 2012). The introduction of Historic Building Information Modelling (HBIM) has achieved sustainable data management in the survey, monitoring, and recording of architectural heritage, demonstrating outstanding advantages that surpass traditional information management methods and generating comprehensive datasets containing multiple data types. Virtual reality (VR) is becoming a more attractive form for public display and value communication in heritage projects. VR provides and replicates immersive environments, simulating physical presence in the real world with high interactivity (Arrighi et al., 2021), play a big role in heritage display. WebVR, as an application category of VR, is published based on web platforms, allowing the public to participate in VR experiences of architectural heritage online through websites and platforms, demonstrating strong public communication potential.

The value inheritance of architectural heritage requires sustainable professional protection and public-oriented value communication, with effective information management and transmission being crucial to achieving this goal. The increasing use of digital technologies can improve information sharing among different users throughout the long-life cycle of buildings (Tucci and Lerma, 2018), helping to achieve continuous and effective information management in heritage protection projects. HBIM has become a powerful information management tool for expert users in heritage projects, however, it is limited by the lack of model interaction and the need for professional software skills and knowledge, making it difficult for non-expert users to access heritage data. VR has transformed the way historical buildings are accessed and visualized, providing immersive experiences for professionals and the public, and enhancing awareness and understanding of heritage buildings. Although the main goal of HBIM is not visualization, its result is a comprehensive 3D model of the structure, opening the door to virtual tours of buildings (Penjor et al., 2024). This demonstrates the potential for joint application of HBIM and VR in architectural heritage projects, where HBIM models can be used to develop immersive environments where users can immerse themselves in a first-person perspective and interact with different types of content (Banfi, 2019). WebVR is published based on web platforms, provides a friendly access experience without professional skills on portable devices, further expanding the application scenarios of VR and the dissemination range of information in heritage projects. Taking Yangxin Hall, a typical example of Chinese official architecture, as a case study, this research constructs an application framework for accessing, managing, and transmitting heritage information using different digital technologies (HBIM, VR, WebVR) according to the work requirements and application scenarios of different stages of architectural heritage protection projects (heritage survey, information recording, monitoring, public exhibition), systematically and accurately meeting the needs of various stakeholders in architectural heritage protection projects.

## 2. Research aims

This research aims to construct an overall framework for the application of digital technologies in different stages of Chinese official architectural heritage protection projects, exploring systematic data collection and processing methods developed by digital technologies from heritage information management to public exhibition. Focusing on the joint application potential of HBIM-VR-WebVR throughout the entire process of architectural heritage protection rather than the application scenarios of a single technology, it aims to achieve the sharing and continuous management of diversified information among different users.

Research aim concludes: obtaining multiple digital assets including 3D digital models through the establishment of architectural heritage information models and developing VR platforms corresponding to different users and needs using the acquired data assets. We Collected user experience data through questionnaires, evaluate the user experience of each platform using multiple indicators, and verify the rationality of the design of each platform and the overall framework based on the evaluation results. By continuously provide services for the protection and information management of architectural heritage and public display through the established platforms, the overall framework can provide a reference for similar architectural heritage protection projects.

## 3. Materials and methods

### 3.1 HBIM as the data foundation

On July 27, 2024, the 46th World Heritage Committee inscribed the Beijing Central Axis architectural complex, including the Forbidden City complex and 15 other architectural heritages, on the World Heritage List, demonstrating their Outstanding Universal Value (OUV). The research object of this paper, Yangxin Hall, which is an important representative building in the Forbidden City complex and a typical example of Chinese traditional official architecture.

Benefiting from HBIM's outstanding information management capabilities, HBIM has been maturely applied in the field of architectural heritage protection. In architectural heritage projects, the HBIM process mainly includes two stages: data collection and object modeling. In the data collection stage, data can be classified into two categories according to their geometric attributes: Non-geometric Data and Geometric Data (Bastem and Cekmis, 2022). The former includes material types, construction techniques, historical data, physical properties, archival data, and historical documents of the research object, while the latter is mainly used to create a 3D model of the research object (Banfi, 2019) (Brumana *et al.*, 2019) (Garagnani, 2013) (Maietti *et al.*, 2018). In previous surveys of Chinese official architectural heritage, several important architectural features related to HBIM geometric data collection have been found: (1) The building volume is relatively restrained, with regular and rigorous shapes, strong geometric properties, and natural curves such as the roof that are easy to grasp. (2) Represented by wooden structures, the building is constructed in units of components, and the main structure of the building has strong regularity. (3) Many building components are hidden above the ceiling, with hidden parts and dead corners that are not easily detected by 3D laser scanning. (4) Some components are small and have exquisite lap-joint relationships. (5) The decorative carvings of building components are relatively restrained, often attached to planar components (Han, 2020).

Therefore, in the collection of HBIM geometric data, the characteristics of architectural heritage are fully combined with the manual survey method of researchers to overcome the shortcomings and defects of 3D laser scanning, further improving the accuracy and efficiency of the data collection process. At the same time, the non-geometric data of architectural heritage is gradually collected and acquired during the manual survey process, and associated and integrated with geometric data. The integration and entry methods of non-geometric data include: (1) Directly selecting components in the Autodesk Revit model for entry; (2) Using the "Bill of Materials" function in Autodesk Revit for entry; (3) Using plugins to export/import information through Excel tables, keeping the table information synchronized with the Autodesk Revit model bill of materials (Han, 2020).

According to these architectural features, a Yangxin Hall HBIM model was constructed, and in this workflow, complete data assets of the target architectural heritage, including geometric and non-geometric data. These data assets will also become the data foundation for constructing each platform in subsequent stages.

### 3.2 Development of VR projects - extended application of heritage information

**3.2.1 Facing expert users: immersive environment for interacting with HBIM assets**: According to the definition of building SMART International, IFC is a standardized and digital description of the built environment (including buildings and infrastructure). As an open international standard, it enables data transmission and sharing among different hardware devices, software platforms, and practical cases with different interfaces (Zhang and Zou, 2022). The import of data completely preserves the topological structure of the 3D model and the building component information based on the IFC standard, and based on this, realizes the mutual mapping of information between the HBIM platform and the VR project. Compared with nonimmersive desktop visualization, it is often argued that immersive VR can better understand scale and details, allowing people to enter and inspect the environment in a way like real life (Han and Leite, 2021). For design review meetings and model inspections, it has been proven to strengthen communication and improve collaboration among participants (Wolfartsberger, 2019).

The VR platform designed for professional researchers of architectural heritage enables architectural researchers to carry out research in an immersive and present way, combining the scene to master the information of ancient buildings and protection projects, and formulate protection plans and decisions. The platform has the functions of interactive retrieval of HBIM information in the VR scene, as well as entity association, information association, component status, and information annotation, to assist professional users in carrying out functions such as data supplementation of the building information platform, phased planning of protection projects, and construction sequence decision-making through online or present immersive perception methods. This annotation information will also realize the reverse mapping of the building information model and data platform information through the data interface. The technical solution will be based on Unreal Engine and Oculus Quest 2. Unreal Engine 4, a game development engine launched by Epic Games, is one of the mainstream software tools for VR project development, and Oculus Quest 2 is an HMD released by Facebook in 2020. The platform design will achieve two aspects of expectations: (1) In data management, the VR platform developed in this paper is based on the IFC standard, realizing real-time two-way information transmission with the building information management platform, and constructing a mapping in the VR platform according to the information hierarchy structure of the IFC standard, so as to integrate and manage various information of the HBIM system through the VR platform, view and modify them uniformly in the VR platform, and promote the efficiency of HBIM information management. (2) Aiming at user needs, combined with interaction design theory, the VR interaction design method for architectural professional researchers was explored, and interaction design was carried out.

Data management: The IFC model file is a unified model format for HBIM, which can store text data in addition to the model itself and can be opened by various HBIM modeling software. According to the application requirements of VR environment visualization, it is necessary to standardize the HBIM model and data, and inspect the integrity and normativity of the model from the following five aspects: (1) The building information model should include the components of the architectural heritage and other contents, with corresponding elements and information, and no repeated or redundant model elements. (2) If the model contains sub-models, all sub-models should be able to coordinate with each other and be complete in content. (3) Model components include numbers stored in the metadata attached to the model components, and this ID is unique. (4) The model fineness of the building information model meets the project requirements. (5) The model file format supports the output of IFC2x3 or IFC4 files.

The data information displayed in the VR scene needs to build an information hierarchy corresponding to the information architecture of the ancient building information management platform according to the IFC standard, to establish a structural mapping for data docking. The non-geometric data of each building component is recorded in the excel form of annotation information and has a unique id as an index, so that the number can be retrieved by the VR platform in the Excel table as a string and read the non-geometric data information related to the component. Users can view and modify non-geometric data in real-time on the VR platform, and the modified data is stored in the excel form of annotation information. Based on the IFC data standard, the annotation information excel form in the VR display and information interaction platform is reversely mapped and written into the HBIM database.

The UI module bears the core user needs of this project: For the non-geometric data that does not need to be modified in the architectural heritage information model, the data should be presented in the VR menu according to the original data architecture and hierarchy. Restoring the data architecture and hierarchy is conducive to researchers efficiently viewing the relevant information of ancient building components in the VR environment according to their original usage habits. For the non-geometric data that needs to be modified and annotated, design a way for users to quickly modify the data by clicking buttons. For example, for the next repair project, whether dust removal is needed, clicking "Yes" modifies the intervention information.

### 3.2.2 Facing public exhibition: collaborative narrative of Multivariate Data in interactive scenarios

The geometric data obtained in the HBIM stage, serving as a digital mapping of architectural heritage entities, faithfully reflecting the topological structure of architectural heritage in the real world. However, complex building structures often appear difficult to understand in the absence of contextual situations, which make audiences lose interest.

Each cultural heritage (site and cultural relic) is endowed with economic, artistic, or historical value. This value is largely not inherent in the cultural relic itself but depends on our understanding of its past (Kersel and Luke, 2015). Creating a context for audiences to understand architectural heritage enables the value of architectural heritage to be more comprehensively perceived by audiences. Narrative has always played an important role in exhibition design (Wolff et al., 2012), whether by strengthening the role of exposed objects through stories or using narrative as a meaningful sequence of information blocks for the entire exhibition (Peponis et al., 2003).

From the perspective of structuralism or mechanistic approach (Mollen and Wilson, 2010), interactivity is viewed as a response to technical attributes, and it is proposed that interactivity can be enhanced through these technologies. Some elements, such as joysticks or more complex haptic devices like gloves or suits, enable users to modify the current state through actions such as grabbing or moving objects (Slater, 2009). From a perceptual perspective (McMillan and Hwang, 2002) (Wu, 1999), interactivity refers to the psychological state of users during interaction with technical tools, which is related not only to the actual interactive ability of the media but also to situational characteristics (Sohn, 2011). Engaging learners in relevant physical activities may produce significant learning benefits (Johnson-Glenberg and C, 2019).

The Yangxin Hall, is one of the palaces with the most layout changes in the Forbidden City during the Qing Dynasty. As the main venue for the ruling activities of the Qing emperors, it contains a large amount of historical information. The historical figures and events mainly include those related to the Tongzhi and Guangxu periods. The VR project needs to not only reproduce the main body of the architectural heritage but also display the historical information behind the main body of the architectural heritage.

The scene design of the virtual reality environment, based on the obtained geometric data of architectural heritage, to ensure the interior decoration and furnishings are faithfully reproduced, including the wall pasting, the style and placement of furniture, and the display of calligraphy and painting decorations.

Different locations of the building, as witnesses to historical events, generate a narrative relationship between the immersive architectural space provided by VR and the audience. The narrative script is the spatial tour flow of the audience in the virtual reality environment, and each node of the tour flow serves as a chapter of the narrative: (1) The entrance of the East Warm Chamber is set as the starting point of the display, and the basic information of the East Warm Chamber is introduced here (the above figure shows node 1); (2) After the introduction, the experiencer can see the throne bed in front and the empress's throne behind it, and combine the time of the curtain system and the emperor's festival sacrifices to introduce the historical figures and events in the East Warm Chamber, and lead to the next display content of the Suian Room (the above figure shows nodes 2 and 3); (3) The experiencer is guided from the throne bed to the Suian Room to introduce the corresponding display content (the above figure shows node 4); (4) Since the route from the Suian Room to the Shouyu Chunhui Room overlaps with routes (1) and (2), the teleportation function will be used to transport the experiencer to the door of the Shouyu Chunhui Room to continue the experience (the above figure shows nodes 5, 6, 7, and 8); (5) After the experiencer watches all the display contents in the Shouyu Chunhui Room, they are guided back to the starting point to understand the large wooden structure and dougong construction of Yangxin Hall (the above figure shows node 9). The storyline unfolds as the audience interacts and explores. In terms of interaction methods, the audience is provided with two choices: (1) An accurate triggering method based on object recognition to achieve interaction between the role and the functional UI. The experiencer touches the UI with the controller, and the special effects after the UI is triggered provide feedback to the experiencer, while the position of the UI interface plays a guiding role for the experiencer. (2) An accurate triggering method based on the spatial coordinate system to achieve interaction between the role and the demonstration function. The location of the display content is marked to guide the experiencer to the marked point, and the accurate triggering of the display function is achieved through the distance judgment of the spatial coordinates. Non-geometric data, as the main medium for interaction and information exchange between the virtual reality platform and the experiencer, requires a high degree of matching between data collaboration and scene. Appropriate data forms are selected for interaction in different scenes to organize and guide the audience's experience and emotions. The basic information of the East Warm Chamber of Yangxin Hall is displayed in the form of text, accompanied by text reading at a suitable speed; historical events such as the curtain system are designed as drama demonstrations with images of historical figures and dubbing, allowing the audience to understand the content of historical events through the dialogue of the characters.

For the reproduction and display of the building itself, a scaled-down building model is used, and the audience can trigger the UI function to interact with the building model, making the building model split or merge, and actively read the names and information of the building components

#### 3.2.3 Broader dissemination and public participation: web-based virtual reality experience

From 2017 to the present, with the emergence and development of WebVR application programming interfaces (APIs), it has become possible and popular to achieve virtual reality on the network, and it has become the focus of attention due to its lightweight, cross-platform, and other advantages (Li et al., 2021).

WebVR is a Web specification that enables virtual reality in browsers (Kraak *et al.*, 2018). By using WebVR, people can experience virtual reality (VR) on web pages without leaving home, getting rid of the previous static and single display form. (Li et al., 2021) The information dissemination realized based on the network platform has significantly increased the dissemination range of data information, allowing more and more public users to experience VR projects on the network platform, making knowledge dissemination easier.

The acceptance of WebVR technology has been evaluated in various environments, such as text browsing in digital libraries (Hahn, 2018) and immersive experience design in virtual museums (Oliver et al., 2019). Learning in a WebVR environment allows users to immerse themselves in a simulated environment using realistic multimedia scenes (Neroni et al., 2021).

PC or smart portable devices also impose restrictions on the scale and form of displayable data. Therefore, for the data assets obtained in the HBIM stage, it is necessary to propose reasonable solutions to integrate them into a suitable platform for display based on PC or smart portable devices.

The workflow will meet the following needs: (1) Sampling the topological structure and non-geometric data of the original HBIM model 3D model to make the data meet the needs of network services and display to non-professionals. (2) Allowing users to browse the project on the PC side and perform simple interactions to obtain information in a proactive manner.

The Datasmith plugin of Unreal Engine is used to import the original building information model. The Datasmith plugin is optimized for the characteristics of architectural industry models and architectural modeling software, optimizing the process of importing models into Unreal Engine, and importing the main hall model of Yangxin Hall from H-BIM modeling software (such as Revit) into Unreal Engine in groups without loss.

In addition, due to the data capacity limitations of web-based WebVR projects for network platform operation and the interaction characteristics of the audience, as well as the confidentiality requirements of some original HBIM data, panoramic image collection of model information is selectively carried out and used as the data source in the WebVR project. The Panoramic Capture plugin of Unreal Engine is used to perform image sampling on the imported model. The Panoramic Capture plugin can perform 720° panoramic still image or video collection on the scene in Unreal Engine.

Use the HDRI Backdrop plugin of Unreal Engine to build the scene, determine the number of HDRI Backdrop instances to be placed according to the number of scenes to be displayed, adjust the spatial positions of each instance in the detail option panel to avoid mutual overlap between instances, import the HDRI images obtained in the previous step into Unreal Engine, select the corresponding scene pictures for each instance in the cubemap option of the detail option panel of the HDRI Backdrop plugin, and adjust parameters such as the compression settings, Maximum Texture Size and Mip generation settings of the HDRI images to improve the image clarity. Use the level blueprint function of Unreal Engine to realize functions such as scene switching and scene information display.

Use the HTML5 platform option of Unreal Engine's packaging project function, obtain all the project files required for deployment on the HTML5 platform, deploy them to the server, and obtain the web-based display page. The display page can be browsed on any device supporting the HTML5 platform.

Figure 1. Pictures From left to right respectively: VR for expert, VR for public, WebVR

## 4. Evaluation

### 4.1 Construction of the evaluation framework

This section determines to construct the evaluation questionnaire framework using three dimensions: availability, communication potential, and learning effect.

**4.1.1 Platform availability: (**ISO 9241-11:(2018)) defines usability as "the effectiveness, efficiency, and satisfaction with which specified users achieve specified goals in a specified context of use".
Effectiveness: Therefore, an effective system enables users to successfully complete tasks with minimal errors. In VR systems, it can be measured by compatibility, which refers to the degree to which the system's behaviours and response match user expectations and consistency with the real world (Kim and Rhiu, 2024). Fluency is the subjective experience of the difficulty an individual experiences in processing information during the information processing process (Zhang, 2010). According to fluency theory, the ease or fluency of cognitive processes affects subsequent cognitive preferences and decisions. Fluency experiences may be influenced by various parameters (e.g., processing speed (Belke et al., 2010).

Efficiency: In terms of efficiency, it can be evaluated through learnability and operability. Learnability refers to the ability of users to quickly learn the usage method of the VR system, and operability refers to the simple and clear interface of the VR system, making it easy for users to operate, so that users can use the least steps to make the system complete the command.

Satisfaction: User satisfaction refers to the comfort for users and others affected by its use. In VR-related research, presence is a widely mentioned concept, and most scholars define it as the subjective experience of "being there" in a technologically mediated environment, and the level of this experience is often related to the degree of immersion. (Li et al., 2024)

**4.1.2 System communication potential:** The Source-Message-Channel-Receiver (SMCR) model is an information communication model proposed by communication scholar David K. Berlo based on the research of Lasswel (Kurtzo et al., 2019). The important contributions of the SMCR model are mainly reflected in two aspects: one is to clearly define the four basic components included in the information communication process, and the other is to systematically analysed the key factors affecting the information communication process and effects from different factors (Zheng et al., 2014). The SMCR communication model divides the communication process into four elements: source, message, channel, and receiver (Chen et al., 2024). Therefore, the communication potential of the system is evaluated from four dimensions: information source, information quality, information channel, and receiver. The compatibility and form diversity of the information source are related to whether the information can be transmitted through more channels. The holding price and popularity of the channel determine the cost in the information transmission process, affecting the breadth of information transmission. The social influence of the receiver and their positive degree in receiving new information will also affect the result of information transmission. The information quality of the platform was evaluated through clearness and effect of model rebuild.

**4.1.3 Learning effect:** A recall test was used to measure the learning effect. The test questions were compiled based on the content displayed in the VR project, and the learning effect was evaluated according to the correct rate of the subjects' answers.

### 4.2 Participants

Researchers posted an advertisement on social media recruiting experimenters in Tianjin University and surrounding communities, explaining the purpose and requirements of the experiment in the advertisement. Before the experiment began, all participants were informed that participating in the experiment was voluntary. Finally, we got effective data of 31 participants (male:16, female:15) in the experiment, meeting our expected effective data.

### 4.3 Apparatus and stimuli

Projects 1 (Facing public exhibition) used head-mounted display devices (HMD), HTC Vive, which provides 1200 * 1080 pixels per eye and a 110° field of view. Project 2 (WebVR) used 23.8-inch LED flat-panel display with a resolution of 1920 * 1080. Project 1 and Projects 2 used a PC with an Intel(R) Core (TM) i7-10875H CPU running at 2.30GHz, an NVIDIA GeForce RTX 2080 Super graphics card, and 32GB RAM to ensure the smooth operation of VR projects during the experiment. The experimental site was a quiet, well-lit room with a flat, obstacle-free floor, ensuring that participants could move smoothly while experiencing VR projects.

### 4.4 Task and procedures

The experiment process was divided into three stages. First, in the preparation stage, all participants were informed of the purpose and process of the study before the experiment began, and a special survey was conducted on the participants to collect their personal information, including age, gender. Then, in the experimental stage, each experimenter would sequentially complete the experience tasks of these two VR projects. Before the experience began, the researchers would demonstrate and explain the use of VR devices to the participants to make them familiar with the operation of the devices. The experience time for each platform was controlled between 5-15 minutes to ensure that participants could completely experience each VR project and prevent them from feeling tired due to the long experiment time, which would affect the experience effect. After completing the experience task, a questionnaire survey was conducted. In this stage, participants would complete the questionnaire survey on the availability and communication potential of these two project, participate in the recall test and recognition test for Projects 1 and Projects 2, and be interviewed openly after the questionnaire survey to ask for their opinions on these two projects.

### 4.5 Measures

The questionnaire questions answered by the participants are divided into three parts based on the framework determined in Chapter 4.1 to evaluate the availability of the platform, the communication potential of the system, and the learning effect. The detailed questionnaire questions are listed in the appendix.

#### 4.5.1 Availability

The availability evaluation of these two projects includes three elements: effectiveness, efficiency, and satisfaction. Effectiveness is evaluated through two dimensions: compatibility and fluency, with two questions for each dimension. Efficiency is evaluated through two dimensions: learnability and operability, with two questions for each dimension. Satisfaction is evaluated through two dimensions: immersion and comfort, with two questions for each dimension. All questions in the availability evaluation use a 5-point Likert-type scale.

#### 4.5.2 Communication potential

The communication potential of these two projects is evaluated through four elements: information source, information channel, information quality, and information receiver. The information source is evaluated through two dimensions: compatibility and richness. The information channel is evaluated through two dimensions: holding price and popularity. The information quality is evaluated through two dimensions: clarity and model reconstruction effect. The information receiver is evaluated through two dimensions: social influence and positive degree of information reception. Each dimension includes two questions, and all questions use a 5-point Likert-type scale.

#### 4.5.3 Learning effect

The learning effect is evaluated through a recall test. The test content is compiled based on the content displayed in Projects 1 and 2, all related to the architectural heritage of Yangxin Hall. The recall test for each project includes two types of questions: multiple-choice questions, and fill-in-the-blank questions.

## 5. Result

### 5.1 Differences between immersive VR and WebVR

Paired t-tests were used to analyze the differences in availability and communication potential between different devices. As shown in the Table 1, in terms of availability, there was a significant difference in effectiveness, specifically, the effectiveness of the Projects 1 group was better than that of the Projects 2. There was no obvious difference in efficiency between the two groups, and in terms of satisfaction, Projects 1 had higher satisfaction than Projects 2.

| Evaluation dimension | Groups | SD | Mean | t | p |
|---|---|---|---|---|---|
| Effectiveness | Projects 1 | 0.46185 | 4.1774 | 2.953 | 0.006 |
| | Projects 2 | 0.70444 | 3.7903 | | |
| Efficiency | Projects 1 | 0.68224 | 4.0565 | -1.436 | 0.161 |
| | Projects 2 | 0.49879 | 4.1935 | | |
| Satisfaction | Projects 1 | 0.39724 | 4.3710 | 8.043 | <0.001 |
| | Projects 2 | 0.69066 | 3.4919 | | |

Table 1. Paired t-tests analysis of availability

In terms of the system's communication potential, web-based VR had greater advantages as an information source than HMD VR, and had more advantages in information channels. HMD VR was superior to web-based VR in information quality and receiver.

| Evaluation dimension | Groups | SD | Mean | t | p |
|---|---|---|---|---|---|
| information source | Projects 1 | 0.65346 | 3.4919 | -3.512 | 0.001 |
| | Projects 2 | 0.49744 | 3.9194 | | |
| information channel | Projects 1 | 0.68224 | 2.9597 | -6.388 | <0.001 |
| | Projects 2 | 0.45805 | 3.7742 | | |
| information quality | Projects 1 | 0.39724 | 3.9597 | 3.327 | 0.002 |
| | Projects 2 | 0.90852 | 3.4597 | | |
| information receiver | Projects 1 | 0.45496 | 4.3468 | 4.815 | <0.001 |
| | Projects 2 | 0.76745 | 3.7742 | | |

Table 2. Paired t-tests analysis of communication potential

### 5.2 Differences in learning effects of VR

There was a significant difference in the recall test results between Project 1 and Project 2 ($Z=-2.286$, $p=0.022$). The paired analysis of the effect differences of 31 participants in the two learning systems was conducted using the Wilcoxon signed-rank test. The statistical results showed that the learning effect of participants in Project 1 was significantly better than that in Project 2. 54.8% of the learners performed better in Project 1, only 16.1% of the learners had an advantage in Project 2, and 29.0% of the learners showed no significant difference, indicating that Project 1 was more effective in promoting knowledge learning.

### 5.3 Experience results of the expert system

Fifteen architectural industry practitioners or researchers were invited to experience and evaluate the expert VR system. The questionnaire results showed that the system performed best in information source and information quality, while satisfaction was significantly low, suggesting that the comfort of the system experience needed to be optimized.

| Evaluation dimension | Minimum | Maximum | Mean | SD |
|---|---|---|---|---|
| Effectiveness | 2.25 | 4.50 | 3.4167 | 0.93859 |
| Efficiency | 1.75 | 4.75 | 3.1000 | 1.00357 |
| Satisfaction | 1.25 | 4.25 | 2.8333 | 0.94334 |
| information source | 2.75 | 4.25 | 3.4500 | 0.50178 |
| information channel | 2.50 | 4.00 | 2.9500 | 0.57632 |
| information quality | 2.50 | 4.50 | 3.4500 | 0.87219 |
| information receiver | 1.50 | 4.50 | 3.4500 | 1.10276 |

Table 3. Availability analysis of communication potential

## 6. Discussion

This study constructed an overall framework for the application of digital technologies in different stages of Chinese official architectural heritage protection projects. Through the joint application of HBIM-VR-WebVR throughout the architectural heritage protection process, multiple sets of VR systems were established to achieve the sharing and continuous management of diversified information among different users.

User experience data was collected through questionnaires, and the user experience of each platform was evaluated using multiple indicators. Compared with studies focusing on technical application details, we provide a more comprehensive and general overall framework. On the other hand, our study further conducted user evaluation on the framework, enabling us to gain a deeper understanding of users' real evaluations and expectations of the system. Overall, the study can provide theoretical references for similar architectural heritage projects.

During the evaluation process, we noticed differences in the evaluation of different platforms in different dimensions, meaning that the joint application of different platforms throughout the architectural heritage protection process can form complementary advantages. Immersive VR experiences can provide the public with better interactive and knowledge-learning experiences, while WebVR can enable the more extensive and low-cost dissemination of architectural heritage information to the public in this process.

## 7. Conclusion

This study systematically established an integrated application framework of HBM-VR-WebVR throughout the entire cycle of architectural heritage protection, developed customized systems for professional protectors and the public using the obtained digital assets, and verified the framework's effectiveness through empirical methods: evaluating platform performance and framework rationality through multi-dimensional user experience questionnaires.

The theoretical contributions in the field of cultural heritage digitization include three aspects: first, proposing an overall framework for the collaborative application of HBM-VR-WebVR, making up for the application limitations of single technologies, and demonstrating the complementary collaborative mechanism in the entire process of heritage protection work. Second, bridging the gap in information sharing between professionals and the public, solving the problem of value transmission from heritage information collection to display, and making the utilization of heritage digital information more complete. Third, establishing an evaluation index system, constructing a multi-dimensional evaluation standard for user experience suitable for heritage digital platforms, and quantitatively evaluating platform performance and framework rationality.

This study also has some universal practical significance for similar official architectural heritage protection projects, providing a path reference for the digital protection of the entire life cycle of architectural heritage and continuously providing theoretical support for the optimization of protection decisions.

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**Appendix**

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