HBIM-Based Digital Restoration and Documentation of Hyeumwonji as Lost Wooden Architectural Heritage

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Abstract

This study presents a Historic Building Information Modeling (HBIM)-based approach for the digital restoration and documentation of lost wooden architectural heritage. The approach was applied to Building 1-2 of Hyeumwonji, the site of a temporary Goryeo Dynasty palace in Paju, South Korea. To reconstruct this lost structure, we combined historical and archaeological analyses to estimate the original design and generated blueprints that guided the HBIM-based 3D model of the building. We collected LiDAR point cloud data from the site, aligned them with the HBIM model, and visualized the integrated result using Unreal Engine 5. The outcome was a comprehensive virtual restoration comprising 13,814 individual building elements. This case study demonstrates that, even with minimal physical remains, wooden heritage sites can be digitally restored by leveraging HBIM and historical reasoning. It also highlights the strengths of HBIM in version tracking, incorporation of historical updates, and systematic documentation throughout the restoration process. Compared to traditional 2D CAD-based restoration methods, the HBIM approach offers significant advantages in terms of updatability, data integration, and long-term preservation of restoration data. Overall, the project illustrates how combining rigorous historical analysis with advanced digital modeling can revive lost heritage architecture in virtual form, providing a rich resource for research and conservation.

1. Introduction

Hyeumwonji (혜음원지, 惠蔭院址) was a temporary royal palace and lodging facility built during the Goryeo Dynasty. Located on the route between Gaegyeong (present-day Kaesong) and Namgyeong (present-day Seoul), South Korea, it served as an important stopover for officials and the king as they traveled between the two cities. Established in 1122 (the 17th year of King Yejong's reign) as a state-operated inn (Won, 원, 院), it later also functioned as a royal palace. However, it was destroyed due to historical events such as the Mongol invasions, and only the building sites remain. Excavations have revealed relics including a pond, drainage channels, and the foundations of 27 buildings on a nine-level terraced site measuring approximately 104 by 106 meters, as well as numerous artifacts such as Buddha statues, roof tiles, and pottery fragments (Institute of Historic Architecture Technique, 2018).

These remains and documentary records confirm that Hyeumwonji is an important heritage site that conveys the lifestyles of the royal family, aristocrats, and commoners during the early Goryeo period. However, the wooden structures were completely lost (Figure 1).

Figure 1. Overview of the Hyeumwonji site.

Traditionally, the restoration of wooden architectural heritage has relied on historical research to produce scale models or partially restore structures using the remaining elements. In some cases, full-scale physical reconstruction is possible using extensive documentary sources. However, in cases such as Hyeumwonji, where surviving architectural remains are extremely limited, the application of traditional physical restoration methods is virtually impossible. This is due to unavoidable constraints, such as a lack of materials, manpower, and resources, as well as the uncertainty inherent to the estimations required during the restoration process. In addition, if further research leads to revisions of the presumed original form, it is difficult to modify what has already been restored.

Therefore, digital restoration has recently received increasing attention (UNESCO, 2003; Hou et al., 2022; Basu et al., 2023). This new approach uses advanced digital technologies to virtually reproduce and document both tangible and intangible cultural heritage to resemble its original state as closely as possible. In recent years, digital restoration projects for lost architectural heritage have increased. Examples include the augmented reality (AR) reconstruction of Hwangnyongsa, the largest Buddhist temple of the Silla era, and the Goryeo Palace Restoration Project, which used joint excavation data from Manwoldae Palace in Kaesong. The outcomes of these projects have been shared at relevant academic conferences (Korea Heritage Service, 2020; Jung, 2021; Al-Muqdadi and Ahmed, 2022).

Wooden architectural heritage is particularly vulnerable to natural environmental factors, deterioration, and fire, resulting in the loss of many examples of cultural architectural heritage. The remaining structures require continuous management. Conventional 2D computer-aided design (CAD)-based records are inadequate for accurately capturing the complex structural details of wooden architecture and have inherent limitations regarding the reliability of restoration proposals. To overcome these limitations, Historic Building Information Modeling (HBIM) technology has recently emerged as a solution (Kang et al., 2023; Kim and Lee, 2024). HBIM is a digital documentation technique that integrates 3D data, such as laser scanning and photogrammetry, with ontology-based semantic information and parametric modeling and is used for the conservation and design of cultural architectural heritage (López et al., 2018). To date, this technique has been mainly applied to cultural architectural heritage that is either fully or partially preserved. However, this study applies HBIM to lost wooden architectural heritage with virtually no surviving remains in an attempt to digitally restore and document it. This approach aims to expand the scope of HBIM applications and explore the possibilities of new methodologies.

Accordingly, this study aims to contribute to future research by systematically documenting both the rationale for restoration estimates and the entire restoration process using HBIM.

2. Related Works

Research on the restoration of cultural heritage using digital technologies has been conducted across various disciplines including architecture, archaeology, and museology. In the field of architectural heritage, BIM technology has evolved from its use in new buildings to its application in existing historical structures, leading to the development of HBIM.

Early HBIM research primarily focused on the scan-to-BIM process, which converts point cloud data acquired through laser scanning or photogrammetry into 3D models. This method enables the relatively rapid and accurate digitization of the shape and spatial information of actual heritage assets and has therefore been applied mainly to historic buildings with substantial physical remains.

In addition, the parametric modeling of distinctive forms and detailed structures of complex historical buildings, along with the documentation of each structural component, has been a significant area of research (Kang et al., 2023). This approach not only incorporates three-dimensional shape data but also integrates various attribute information (such as material, construction technique, period, and function) for each component into the digital model. Another important strand of early HBIM research involved the manual creation of 3D models based on two-dimensional records such as measured drawings, historical documents, plans, documented structural diagrams, and other archival sources (Korea Heritage Service, 2021; Adami et al., 2023). In cases where little or only partial physical evidence of a historical structure remains, 3D models are often constructed virtually by interpreting documentary sources, old plans, and pictorial records. While such manual modeling allows greater room for interpretation and inference than scan-based methods, it consequently increases uncertainty in the restoration results. Nonetheless, this approach remains unavoidable for digital documentation and restoration of heritage sites with minimal physical remains.

Accordingly, early HBIM research was developed using a combination of scan-data-based automated or semi-automated modeling techniques, researcher-driven manual modeling based on the interpretation of records, and the construction of semantic data encompassing structural and historical information.

Since 2021, the Korea Heritage Service has led HBIM construction projects for architectural heritage in Korea, and digital restoration efforts to lost traditional architectural heritage are gradually increasing (Korea Heritage Service, 2021). In addition to the aforementioned AR restoration of Hwangnyongsa and the Manwoldae Palace restoration project in Kaesong, various R&D projects are underway to restore the lost heritage using technologies such as augmented reality (AR), virtual reality (VR), and 3D scanning. However, cases in which HBIM techniques have been fully applied are rare.

In particular, research on the application of HBIM in situations in which almost no physical structure remains is still at an early stage. Against this background, the present study aims to expand the scope of existing research by proposing an HBIM-based restoration strategy for lost wooden architectural heritage sites.

3. Research Methodology

Restoring wooden architectural heritage sites that have been completely destroyed, leaving only archaeological remains, involves a high degree of uncertainty owing to the lack of structural information and limitations in historical literature. In such contexts, the effective application of HBIM requires systematic documentation of both the resources used and the reasoning behind the restoration decisions. This study aims to address the limitations of conventional document-based restoration methods by empirically supplementing them with HBIM in these special circumstances. For this project, given the extremely limited remains and the structural complexity inherent to wooden architecture, precise documentation and management of the rationale behind each restoration step are deemed essential.

The research methodology consisted of five sequential stages.

First, relevant historical records and prior research were analyzed to establish a basis for restoration.

Second, on-site surveys and 3D scanning were conducted to capture site information.

Third, HBIM was used to digitally reconstruct the building.

Fourth, the digital model was visualized in a real-time rendering environment.

Finally, all decisions and uncertainties were systematically documented for future studies.

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Data Collection and Analysis: This research began with an investigation of major historical sources related to Hyeumwonji from the Goryeo Dynasty era (Kim, 2009; Yoon, 2010; Institute of Historic Architecture Technique, 2018; Korea Heritage Service, 2020; Jung, 2021). All floor plans, remains, photographs, and records obtained from excavations conducted between 1999 and 2004 were collected. Where data were lacking and assumptions were required, we referred to studies on similar structures with comparable functions from the same era, as well as existing academic and historical research on Hyeumwonji. Based on this research, restoration plans for the layout, spatial organization, and structural system of Building 1-2 were reviewed from multiple perspectives; these plans served as the foundation for the design assumptions of the HBIM model. This approach was intended to ensure that the restoration model would reflect as wide a range of historical evidence as possible, rather than relying on any single source or hypothesis. (Dankook University Institute of Burial Cultural Properties, 2006; Yoon, 2010; Institute of Historic Architecture Technique, 2018).

Field Survey and 3D Scanning: Field surveys were conducted to observe the remains of Building 1-2 at Hyeumwonji in person in order to complement the documentary sources. An iPad-based LiDAR scanner was used to scan the topography and expose foundation stones around the site, producing point cloud data and image-based 3D models. The scan data included information, such as the shapes, dimensions, and relative positions of the foundation stones, which could only be acquired onsite.

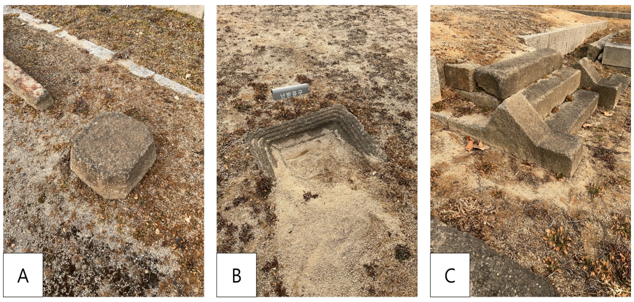

Figure 2. Field survey photographs of Hyeumwonji Building 1-2 (A: Base Stone (*Choseok*), B: Remains of a heating system (*Nangbang Yugoo*), C: Stairs).

The scan data were used to align the HBIM restoration model. The degree of spatial correspondence between the centroids of the foundation stones in the scans and the lower ends of the columns in the HBIM model was verified quantitatively and designed to enhance the reliability of the restoration plan. Although the use of a small mobile LiDAR scanner is advantageous in terms of accessibility and convenience, it is less precise than fixed, high-end scanners. This highlights the need for further fieldwork and acquisition of higher-resolution data in the future.

HBIM Modeling: Design drawings were created using BIM software (SketchUp and Autodesk Revit) based on a literature review and field measurement results. The site topography and foundation stones of Building 1-2 were positioned based on their precise coordinates. Columns were erected on the foundation stones, and the shape (cylindrical), bracket style (multiple bracket types), column height, ceiling height, and member dimensions were estimated with reference to Goryeo-period public buildings and similar sites (e.g., Manwoldae and Anhakgung at Kaesong, North Korea). The main horizontal members (Changbang, Pyeongbang, and Daedulbo) were placed above the columns, and the roof structure was built in the traditional Korean style and finished with traditional tiles. The internal spatial arrangement was implemented based on available clues regarding the locations of the walls and rooms. Elements missing from the original structure were introduced only minimally and only when supported by existing data. The completed HBIM was designed to function as a structural and informational digital archive by integrating the dimensions, spatial data, and design rationale of each member.

Digital Visualization: The completed HBIM model was imported into Unreal Engine 5 for high-resolution visualization in a real-time rendering environment. The materials, lighting, terrain, and natural light were simulated in accordance with traditional Korean wooden architectural styles. A first-person camera was set up to enable the users to freely explore both the exterior and interior spaces within the virtual environment. This first-person viewpoint was designed true to scale so that it could later be used for VR/AR applications. Based on archaeological remains, the interior floor structure was presumed to include a heating system; however, owing to a lack of clear evidence or studies on the precise structure of the floor, this was not implemented in the current version. Digital content was created with extensibility for potential use in AR applications on the site and in online virtual museums. They can also serve as a platform for sharing restoration outcomes and collecting feedback from researchers and the public (Kim & Lee, 2024).

Documentation and Management Processes: The HBIM model developed in this study served as a digital document for the restoration of Building 1-2 at Hyeumwonji based on historical and structural evidence. The HBIM model and game engine-based visualization outputs can be utilized in a variety of ways for future academic research and educational purposes. Uncertain or interpretive elements are tagged as "estimated" within the HBIM model for ease of subsequent study and data integration. Because the restoration model was built as an HBIM composed of individual components, future improvements and modifications can be easily incorporated and documented. This approach overcomes the limitations of traditional 2D designs and document-centric records by providing a multi-dimensional data-driven methodology for heritage restoration and management.

4. HBIM of Building 1-2 at Hyeumwonji

This section details the HBIM modeling process described in the previous steps. Building 1-2 is presumed to be a central building within Hyeumwonji, with wing buildings on either side situated on the same ground level. Excavations revealed that the site comprised three rectangular building foundations corresponding to these structures. The foundation of the central building consists of four columns oriented east–west and four columns oriented north–south. Each wing building has a foundation of three columns oriented east-west and four columns oriented north-south. Of all the remains in Hyeumwonji, this site is considered to be in the best state of preservation. Hyeumwonji’s main building complex is regarded as playing a central role. Furthermore, its floor plan and structural characteristics are similar to those of contemporary Goryeo-era buildings, such as the Anhakgung Palace Site in Pyongyang and the Goryeo Palace Site in Kaesong. For these reasons and because digital reconstruction is relatively

straightforward, this structure was selected as the main subject of this study (Hou et al., 2022; Basu et al., 2023).
The modeling process consisted of the following three steps.

First, the floor plan and structural layout were designed based on previous academic studies of Hyeumwonji and on-site surveys with reference to historical records and similar architectural cases to ensure the validity of the restoration.

Second, based on the finalized design, the major building components (stylobate, foundation stones, columns, and beams) were modeled using the BIM software, and data for each component were recorded.

Third, point cloud data acquired through onsite 3D scanning were integrated into the HBIM model. This allowed the cross-verification of the survey data, historical records, and model to refine and ensure consistency.

Structural Estimation and Architectural Drawing Design: Based on layout information from previous academic studies and on-site surveys at Hyeumwonji, the floor plan of the central building consisted of three bays across the front and three bays along the side. Each wing building was designed as an *ondol* room (heating room/bedroom) with two bays across the front and three bays along the sides. This floor plan and spatial arrangement were developed based on the spatial structure and scale of temporary palaces described in historical documents, as well as architectural examples of similar functions from the same period, such as the Anhakgung Palace Site, Manwoldae in Kaesong. Building 1-2's detailed design was based on this composition, which served as the foundation for creating the HBIM model. Various documents, excavation remains, and comparable architectural examples were reviewed throughout the design process to ensure the validity of the restoration. Key structural features, such as the arrangement of columns, beams, and roof structures, were incorporated into drawings based on existing remains and academic research. In particular, owing to the characteristics of the archaeological remains, the two side wings are positioned further forward than in the central building, resulting in an asymmetric layout. This distinctive spatial configuration, in which the side wings project beyond the front of the central hall, is clearly reflected in the restoration model.

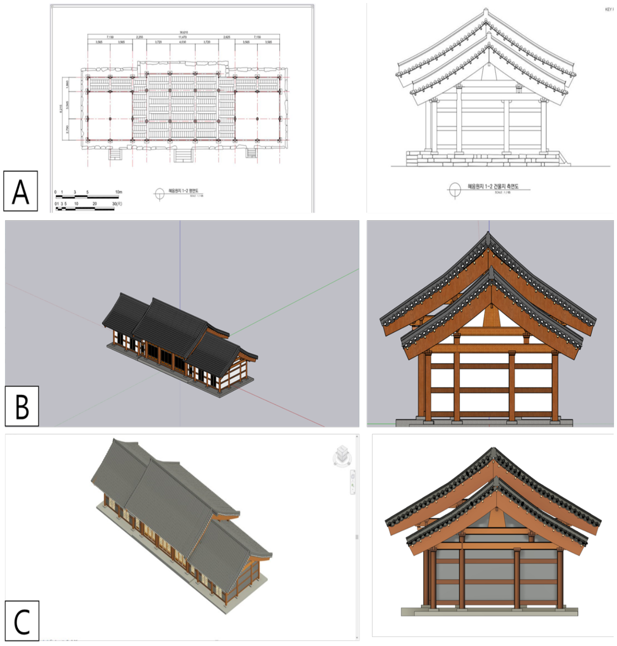

Figure 3. 3D restoration process for Hyeumwonji Building 1-2 (A: Restoration drawing production, B: 3D modeling, C: HBIM modeling).

3D Modeling: Based on the finalized floor plan and structure, the main architectural elements, such as the stylobate, foundation stones, columns, and beams, were implemented as HBIM models. For structural elements that no longer exist (e.g., columns, beams, and joinery), the design was informed by the representative styles of the Goryeo-period public architecture, such as circular-section columns, multiple-bracket sets, and traditional roof forms. Wherever possible, the dimensions and connection methods for each component were derived from surviving remains and comparable sites, such as Manwoldae in Kaesong and the Yeongamsa Temple Site. Areas lacking clear data were addressed through minimal assumptions or marked as "estimated." For interior spaces, such as windows and finishes, only basic walls and room partitions were implemented because of insufficient detailed information, with room function and placement restored based on existing literature and excavation remains. BIM software such as SketchUp and Autodesk Revit were used to create the HBIM model. This model incorporates the structural information, design rationale, and property data for each component. The HBIM extends beyond simple 3D geometry by recording the dimensions, materials, spatial relationships, and design rationale of each component as data. This integrated information provides a basis for analysis, documentation, and management (Kim, 2009; Yoon, 2010).

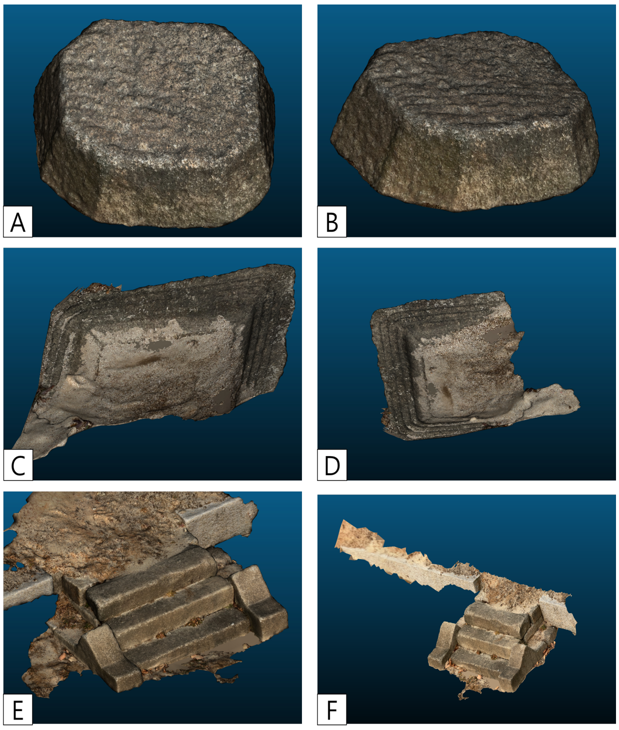

Figure 4. 3D scan models of the key archaeological remains of Hyeumwonji Building 1-2.

A, B: 3D scan models of the foundation stone archaeological remains of Hyeumwonji Building 1-2.

C, D: 3D scanned models of the archaeological remains of the heating system at Hyeumwonji.

E, F: 3D scan models of the archaeological remains of stairs in Hyeumwonji Building 1-2.

Integration of On-site Data: Point cloud data obtained from on-site 3D scanning were merged into the HBIM restoration model and analyzed to ensure that the model accurately reflected spatial elements, such as the positions of the actual remains and foundation stones. The coordinates of the foundation stones from the point cloud data were quantitatively compared with the column positions in the model. The average error and degree of alignment were evaluated repeatedly to enhance the reliability of the restoration design. Discrepancies between survey measurements and the model or uncertainties in the data (e.g., displacement of remains, scale reference errors, etc.), were tagged as "estimated" within the HBIM model, with separate annotation and documentation of supporting evidence. Areas where the upper structural elements were completely lost were left unmodeled to be supplemented in the future, as subsequent research and excavations provide new data. Through the iterative cross-verification of field measurements, historical literature, and the digital model, we maximized the reliability and objectivity of the restoration process. This multilayered documentation and verification structure can serve as a reference for future HBIM-based digital restoration research and provide a dataset applicable to a variety of academic and practical fields.

As shown in Figure 5, the integration of the photogrammetric 3D scan model, point cloud data, and HBIM-based model within Unreal Engine provides a comprehensive digital dataset of the restoration process. This combined model can serve as a digital resource for future research.

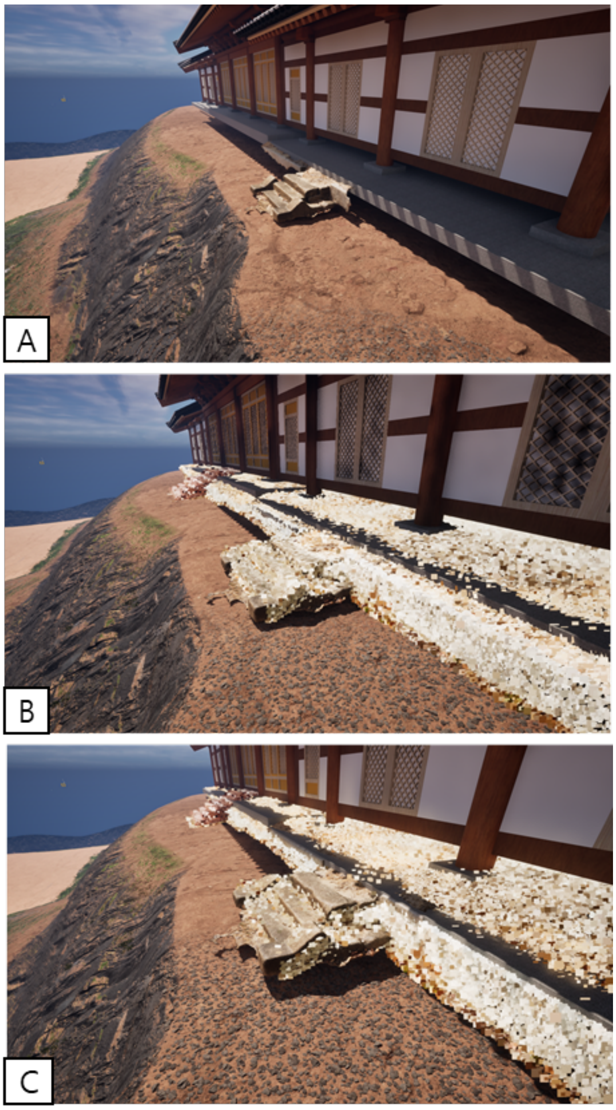

Figure 5. Integration of 3D scanning data and HBIM-based models in Unreal Engine.

A: Comparison between the photogrammetric 3D scan model and HBIM-based model.

B: Comparison between the point cloud model and HBIM-based model.

C: Visualization obtained by integrating A and B.

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5. Digital Restoration Result and Discussion

This section presents and discusses the completed digital restoration model based on the HBIM. This discussion focuses on the following three aspects.

First, real-time visualization using Unreal Engine.

Second, verification and comparative evaluation of analogous architectural heritage.

Third, research and practical implications are discussed, as well as the limitations of the restoration results.

HBIM-based Digital Content Creation and Utilization: Using an Unreal Engine for real-time visualization significantly improves the ability of the HBIM model to render visual elements, such as lighting, terrain, and textures. Users can freely explore both the exterior and interior spaces of a restored royal villa in a VR environment. This virtual experience enables users to accurately perceive the size, layout, and internal structure of major spaces, such as ondol rooms, with a high degree of realism. This approach provides a sense of space, circulation, and immersion that cannot be easily understood using simple blueprints or 3D models. It also serves as an effective visual aid to explain the form and structure of architectural heritage to visitors and researchers. In this study, we aimed to enhance realism using high-quality graphics and detailed simulations. As such, these digital visualizations can be used not only for expert research, but also as valuable digital cultural heritage content for public engagement.

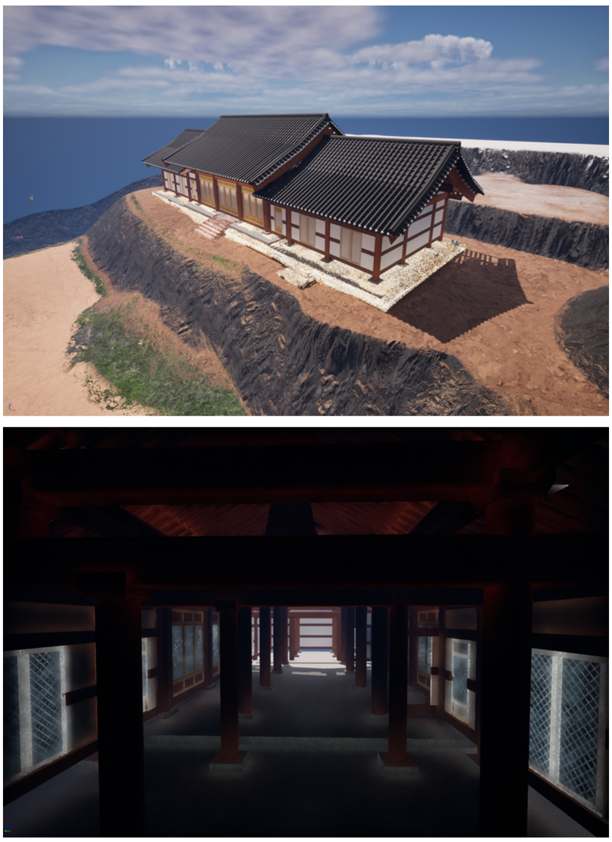

Figure 6. Virtual restoration model of Hyeumwonji digital visualization in Unreal Engine 5.4 (Top: Exterior, Bottom: Interior).

Verification and Comparative Evaluation of Restoration Proposals: To improve the reliability of the restoration, a comparative study was conducted between the Hyeumwonji royal villa and similar Goryeo-era buildings, especially Janghwajeon, at Manwoldae in Kaesong. In the restoration of Janghwajeon Hall in Manwoldae, a grid of 9 × 5 bays was designed based on the standard unit of one *cheok* (approximately 31 cm), and the *Ju-simpo* bracket system was applied. This demonstrates that the floor plans and structural methods were similar to those of the buildings in Hyeumwonji. Notably, a 312-mm standard ruler was unearthed in the northwestern building complex of Manwoldae, providing tangible evidence for the actual measurement units used.
In previous academic studies of the Hyeumwonji building site, the basic *cheok* intervals were reported to be 314 mm (Analysis A) and 330 mm (Analysis B) (Institute of Historic Architecture Technique, 2018). However, in this study, by comprehensively examining the measured data of field survey 3D scan results and excavation results data from Manwoldae, the standard *cheok* was set to 311 mm for 3D modeling.
As a result, compared to the previously suggested 318 mm standard in Hyeumwonji studies, the spacing between buildings increased from -47 mm to 99.3 mm. The error in *yangtong* (length measured along the building’s lateral side) was reduced by an average of 17.7 mm, whereas that in *doritong* (length measured along the building’s front side) increased by approximately 50 mm. We reviewed the validity of the key design elements (e.g., floor plan and structural system) through comparative analysis. This verification process ensured that the restoration model could be used for academic purposes within reasonable limits. However, some elements, such as unconfirmed foundation locations and upper structural details, remain uncertain owing to the lack of physical evidence. These components were modeled based on the literature and comparable cases, and their uncertainties were explicitly tagged in the HBIM model for future refinement.

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Figure 7. Point cloud capture and digital reconstruction of the archaeological remains of Hyeumwonji Building 1-2.

A: Point cloud capture of archaeological remains of Hyeumwonji Building 1-2.

B: Estimated locations of foundation stones based on point cloud captures.

C: Digitally reconstructed foundation stones and point clouds of Hyeumwonji using Unreal Engine 5.

Results of the Restoration Model: In this study, we created a 3D digital restoration model of Building 1-2 at Hyeumwonji based on HBIM. The model visualizes the floor plan, structural type, and roof form of early Goryeo Dynasty villa architecture. It digitally documents the shape, dimensions, and attribute information of each architectural component along with supporting references. Using the HBIM model, researchers can systematically analyze the dimensions and basis of each component design and create outputs such as drawings, part lists, and structural analyses. The completed model consists of approximately 13,814 individual elements, serving as a detailed catalog and quantitative research resource for traditional wooden architecture. Furthermore, HBIM and 3D-scanned models can be integrated with digital visualization platforms such as Unreal Engine, enabling realistic representation of the building’s exterior, interior, and structural details in a virtual space. As the model was structured using HBIM, each building component could be individually disassembled and reassembled within an Unreal Engine environment, as shown in Figure 8. This functionality supports detailed analysis and interactive visualization of architectural elements. These outcomes lay the groundwork for creating various cultural heritage content, including public virtual site tours and AR/VR exhibitions, and extend beyond academic research (Innocente et al., 2023).

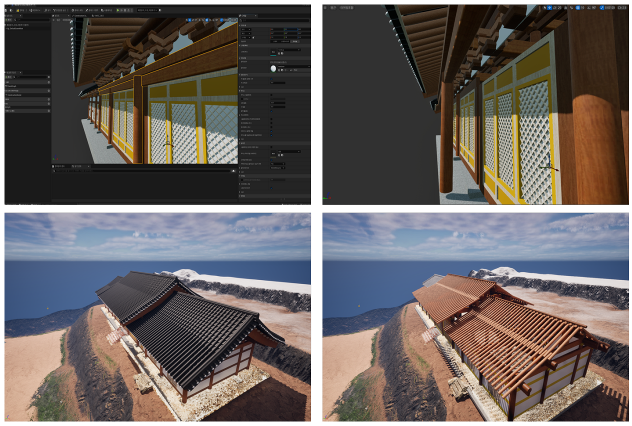

Figure 8. HBIM-based digital visualization model constructed using Unreal Engine 5.4.

6. Conclusion and Future Work

This paper presents a case study that applies a HBIM-based digital restoration and documentation approach to wooden architectural heritage sites. We applied this approach to Building 1-2 at Hyeumwonji in Paju, which was mostly lost and survived as partial remains. By combining traditional academic sources and historical documents with 3D scanning and digital visualization, this study demonstrates that a more precise and systematic approach to restoration and documentation is possible compared with previous 2D plan-based methods.

The HBIM developed in this study serves as a comprehensive digital record that integrates architectural, historical, and spatial information. This information also serves as foundational data for future research, conservation, and structural analyses of similar cultural heritage sites. The HBIM model shows strong potential for broader public and educational use as a basis for digital visualization and content creation. Systematic HBIM documentation enables comparative analysis, the rapid integration of new research, and immersive heritage experiences for the public.

Looking ahead, the scope of digital restoration should be expanded to encompass all remains at Hyeumwonji, with increased multidisciplinary collaboration to improve accuracy and reliability. Minimizing the restoration errors through high-precision scanning and collaboration with BIM experts remain important goals for future studies (Samadzadegan et al., 2023).

Digital restoration is currently used as a supplementary tool to physical restorations. However, this study demonstrated that systematic HBIM procedures can be practically applied to record, restore, and manage severely damaged or lost wooden architectural heritage sites. HBIM offers higher accuracy than traditional approaches by providing integrated digital records. Further, it enables the production of digital content using game engines, thereby enhancing the preservation and public accessibility of cultural heritage sites.

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