Photogrammetric and Semantic Reconstruction of Architect Sinan's Ayakapi Hammam: Reversing Inappropriate Interventions through HBIM

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Abstract

Digital technologies have become crucial tools in the documentation, analysis, and preservation of built heritage, particularly for historically layered structures that have undergone prolonged transformation and intervention. Photogrammetry and information-based modeling have significantly enhanced the ability to record architectural complexity while supporting interdisciplinary conservation practices. The present study utilizes photogrammetry-based Heritage Building Information Modeling (HBIM), scan-to-HBIM, as a tool to understand architectural continuity, deterioration, and transformation in the Ayakapi Hammam (1582), understudied work by the imperial architect Architect Sinan. Through this digital representation, this study proposes a reverse reconstruction approach to recreate an idealized state of the heritage structure which has not been conserved for several decades. TInappropriate modern interventions are digitally removed, and the hammam's architecturaş configuration is virtually reconstructed based on historical, material, and spatial evidence while accounting for natural aging process and material deterioration under protected conditions. The findings demonstrate that scan-to-HBIM based digital models functions not solely as documentation tools but as transparent and transferable decision support systems. By explicitly integrating uncertainty and temporality into the digital model, the proposed approach contributes to a more informed interpretation of long-term architectural transformation and supports conservation decision-making processes grounded in authenticity.

1. Introduction

Architectural heritage stands as a tangible embodiment of cultural memory, authenticity, and collective identity. Yet, heritage structures are increasingly threatened by neglect, incompatible restorations, and loss of integrity over time (Jigyasu, 2016).

The Nara Document on Authenticity (1994) defines authenticity as the degree to which the cultural value of a heritage place is truthfully and credibly expressed through its identifiable attributes. These attributes may include form and design, materials and substance, use and function, traditions and techniques, as well as location, setting, spirit, and other intangible dimensions.

Given that many of the attributes central to authenticity, particularly form and design, materials and substance, construction techniques, and spatial organization, are materially embedded and often vulnerable to alteration or loss, their consistent assessment requires documentation approaches capable of capturing architectural evidence with high precision and interpretive clarity. The increasing demand for accurate, multi-layered records that can support authenticity-based conservation practice has therefore emphasized the need for advanced digital methods that go beyond conventional surveying techniques.

Therefore, digital technologies such as photogrammetry and Heritage Building Information Modeling (HBIM) have emerged as transformative tools for documentation, analysis, and interpretation of architectural heritage (Brumana et al., 2017). Although photogrammetry has been widely applied in international research on cultural heritage (Barazzetti et al., 2022; Garramone et al., 2023; Remondino, 2011), its systematic use in the conservation and preservation of heritage structures in Turkey has been relatively understudied (Bekar and Kutlu, 2024). The Scan-to-BIM approach is a relatively new methodology that enables the conversion of raw data obtained from photogrammetric measurements into an intelligent structured model where all components are linked to a digital information system. This process provides an undeniable advantage in managing, extracting, and updating the geometric and non-geometric information of existing buildings at any time (Aricò & Lo Brutto, 2022).

HBIM models derived from the scan-to-BIM approach enable the integration of heritage building studies into the workflow and allow for the utilization of all the advantages provided by BIM (Rocha et al., 2020). HBIM aims to provide the most comprehensive information possible about the structure, enabling strategic interventions for sustainable practices to ensure the preservation of authenticity based on cultural and historical heritage value. This holistic approach plays a critical role in developing effective conservation measures while preserving the authenticity of heritage structures (Logothetis et al., 2015). Hu et al. (2024) and Garcia-Gago et al. (2022) emphasize the critical importance of pre-restoration digital models and HBIM-based data integrity. Both studies demonstrate that digital models are not merely documentation tools, but rather decision support systems that prevent data loss and guide restoration decisions.

Building upon the geometric documentation capabilities of photogrammetry and HBIM, this study adopts a semantic reconstruction approach in which architectural elements are enriched with historical, typological, and interpretive information derived from archival photographs, historical drawings, academic theses, and comparative analysis of hammams of similar typology. All retrieved information is embedded within the HBIM environment, enabling architectural components to be represented as information based entities rather than purely geometric forms.

In this study, inappropriate modern interventions are digitally removed through a scan-to-HBIM approach and applied to a heritage structure, Architect Sinan's Ayakapi Hammam, which has not undergone conservation or restoratation for approximately six decades. This approach further explores how the structure might have evolved if it had undergone a process of aging consistent with established conservation principles. Rather than proposing a physical restoration, the study adopts a reverse reconstruction approach as an analytical framework. Within this framework, the hammam's architectural configuration is virtually reconstrycted on the basis of historical, material, and spatial evidence, given in Chapter 2, while accounting for natural aging and material deterioration under protected conditions. Due to the absence of comprehensive prior studies and detailed three-dimensional documentation of the Ayakapi Hammam, this research operates within a context of limited empirical data. This limitation is deliberately reframed as an experimental framework in which photogrammetry, Scan-to-HBIM workflows, and HBIM-based information modeling are employed in Chapter 3 to construct a virtual twin of the structure. Through this virtual twin, architectural knowledge derived from different historical phases, particularly the fifteenth and twenty-first centuries, is systematically encoded and interpreted. The resulting reverse reconstruction model is discussed in Chapter 4, while Chapter 5, presents the conclusion of the research.

2. The history of Ayakapi Hammam

The Ayakapi Hammam (bath) designed by the imperial architect Mimar Sinan, stands as a remarkable yet understudied example of Ottoman bath architecture (Eyice, 1997; Kuruçay, 2011). It is located on the southern shore of the Golden Horn and was commissioned in 1582 by Sultan Nurbanu, as part of a charitable foundation (vakıf) (Eyice, 1997). Functioning as a public facility, the bath once played an important role in the social and architectural memory of its urban context.

The hammam was functionally built as a single unit (only for males) and constructed with ashlar masonry walls strengthened by brick bonding courses. A three-part entrance hall (vestibulum) is located in front of the apodyterium, shown in Figure 1, where the lateral compartments are covered with mirrored vaults and the central compartment with a domed vault. The apodyterium itself is square in plan and covered by a large central dome. On the exterior facade, two rectangular windows with marble frames and iron grilles are surmounted by three upper openings, comprising a pointed arched central window and two round arched side windows.

The tepidarium functions as a spatially constrained transitional zone and is covered by a combination of domes and vaults (Eyice, 1997). The caldarium of the Ayakapi Hammam is organised according to a four-iwan cruciform plan scheme, a spatial configuration that represents one of the most characteristic typologies employed by Mimar Sinan in his hammam designs (Eyice, 1997). This scheme, defined by a centrally domed hot space articulated by four iwans aligned along the principal axes, establishes a clear spatial hierarchy and functional differentiation between the central volume, the iwans, and the corner khalwa. In Figure 2, four-iwan hammam typology is shown illustrating other hammam examples.

A comparable spatial organisation is observed in both the Ayasofya and Suleymaniye Hammams, which are among the most representative examples of Sinan's mature period bathhouse architecture. In the Ayasofya Hammam, the four-iwan caldarium is characterised by a strong axial emphasis and relatively deep iwans, which reinforce directional movement and spatial legibility. Similarly, the Suleymaniye Hammam adopts the same cruciform scheme; however, the iwans are more evenly proportioned, contributing to a more centralized and balanced spatial composition. Based on Sinan's four-iwan hammam typology, the iwans are generally covered with vaults, while the corner khalwa are covered by domes. This established pattern provides a key reference for interpreting the original spatial and structural configuration of the Ayakapi Hammam (Eyice, 1997).

Within this comparative framework, the Ayakapi Hammam can be understood as adhering to the same four-iwan typological principles evident in the Ayasofya and Suleymaniye Hammams, albeit at a more modest scale and with a simplified spatial articulation. The reliance on the four-iwan scheme, combined with the domed khalwa and vaulted iwans, situates the Ayakapi Hammam firmly within Sinan's established bathhouse typology, while variations in proportion and spatial emphasis may be interpreted as responses to site conditions, patronage, and functional requirements rather than deviations from the canonical model.

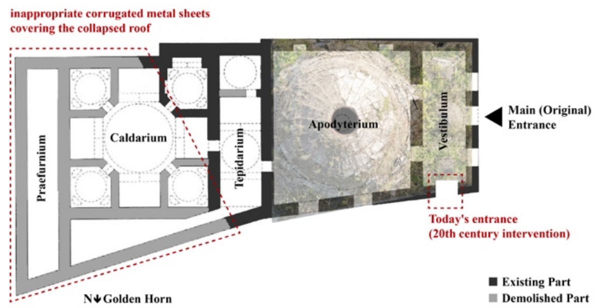

Figure 1. Plan Scheme of Ayakapi Hammam Adapted from Eyice, 1997.

While the architectural configuration of the Ayakapi Hammam situates it firmly within Mimar Sinan's four-iwan bathhouse typology, this typological and cultural significance has not ensured its sustained protection or continued public use. Instead, the building's later history reflects broader processes of socio-economic transformation, in which historic bathhouses have increasingly been detached from their communal functions and reframed as commodified assets within contemporary urban contexts.

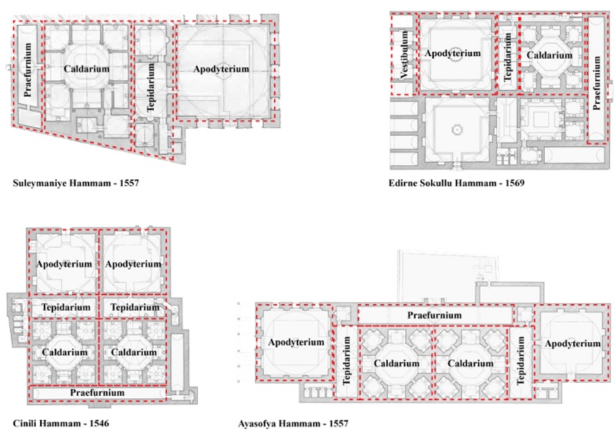

Figure 2. Examples of Four-Iwan Cruciform scheme Hammam Typologies Adapted from TTK, 1989.

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Over time, however, the hammam lost its communal function. It was gradually transferred into private ownership, mismanaged, and ultimately abandoned (Özbek Eren, 2000). But it is found that the architectural plan, structural form and elements of the hammam (such as domes and vaults) are visible in the aerial photograph dating to 1960, as shown in Figure 3, indicating that theses features were preserved up to that period. In recent years, the building was sold for approximately $2 million, symbolizing the commodification of cultural heritage and its detachment from public meaning (AA, 2024). This shift in ownership entailed not only a legal transformation but also the erosion of collective memory and local identity. As a result of inadequate maintenance, unplanned interventions, and prolonged neglect, the structure has undergone severe physical deterioration: vaults have collapsed, walls have cracked due to moisture, cement-based repairs have damaged the original masonry, and many openings have been sealed or altered.

Figure 3. Plan sheme diagram of Ayakapı Hamam superimposed on a 1960 aerial photograph Adapted from Özbek Eren, 2003.

3. Methodology

The methodology is structured as a multi-stage process. First, a virtual reconstruction of the sixteenth-century hammam is developed based on architectural drawings, restitution projects, and historical photographs. Second, the current condition of the hammam is documented through a photogrammetric approach employing UAV imagery and 360° panoramic photography. Third, the acquired data are integrated into the creation of a HBIM. Finally, unnecessary or incompatible interventions are identified and virtually reversed within the HBIM environment, enabling a critical assessment of the structure's original configuration and subsequent alterations.

3.1 Virtual reconstruction of the 16th century Ayakapi Hammam

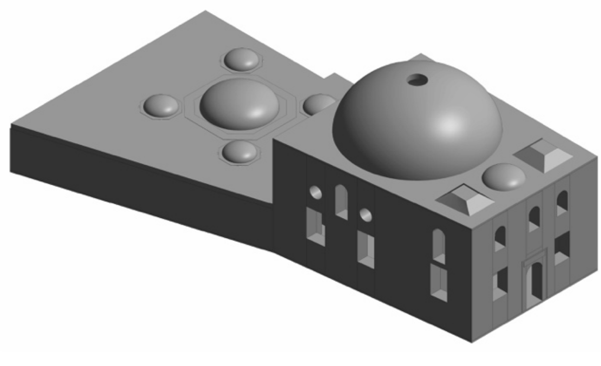


Figure 4. 16th century Ayakapi Hammam Model.

The LOD 100 virtual reconstruction of the Ayakapi Hammam was developed through a critical examination of survey drawings documenting the works of Mimar Sinan, prepared by Ali Saim Ülgen (TTK, 1989). Although Ülgen's documentation provides detailed survey drawings for numerous hammams attributed to Sinan, no direct survey drawings or measured documentation were found for the Ayakapi Hammam. This absence necessitated the adoption of a typological and comparative reconstruction strategy.

Accordingly, hammams exhibiting comparable plan typologies and attributed to Mimar Sinan were systematically analysed and employed as analogical references in the LOD 100 modelling process, see Figure 4. In particular, the four-iwan cruciform plan scheme, widely recognised in the literature as a characteristic feature of Sinan's bathhouse architecture, was selected as the primary reference for reconstructing the probable original spatial configuration of the Ayakapı Hammam. Existing scholarly sources related to the building, including the survey drawings produced in 2000, were adopted as the main academic references, while a 1960 aerial photograph in the same reference constitutes the earliest available visual record documenting the overall massing and footprint of the structure (Özbek Eren, 2000).

While the vestibulum and apodyterium sections of the hammam have largely survived, the caldarium and praefurnium spaces have suffered substantial losses in both structural and spatial integrity due to the collapse of their upper coverings. Therefore, the surviving tromps supporting the western khalwa served as a critical architectural reference. These elements provided tangible geometric and structural evidence for estimating dome heights, spans, and transition systems. The reconstruction of the collapsed volumes was therefore informed by a combination of surviving architectural traces, typological comparisons with analogous four-iwan hammams, and the available documentary sources, ensuring that the LOD 100 model reflects a theoretically grounded and academically transparent interpretation rather than a definitive reconstruction.

3.2 Photogrammetric approach: current situation of the structure

The current physical condition of the Hammam is documented through an integrated photogrammetric survey combining aerial photographs acquired via UAVs and panoramic photographs captured through a 360° panoramic camera. In total, 110 aerial photographs were acquired by UAV, while 472 panoramic photographs were obtained using the 360° panoramic camera. All datasets were processed using Structure-from-Motion (SfM) and Multi-View Stereo (MVS) algorithms to generate a high-density 3D point cloud point cloud that accurately represents the geometry and surface texture of the building, shown in Figure 5.

(a) (b)

Figure 5. a) Point Cloud from UAV b) Point Cloud from 360° panoromic camera.

Post-processing was carried out using Agisoft Metashape and Autodesk ReCap Pro. UAV and panoramic photogrammetric datasets were geometrically aligned and registered within a unified coordinate system to ensure spatial consistency and scale accuracy. Noise filtering and outlier removal operations were applied to eliminate erroneous or redundant data points produced during the SfM and MVS reconstruction. The cleaned point cloud was subsequently imported into ReCap Pro, where further refinement, segmentation, and mesh optimization were performed to improve surface continuity and geometric unity, resulting in a high-fidelity digital representation of the existing state.

The point cloud datasets obtained from the UAV survey and the 360° panoramic camera were imported into CloudCompare software, where a cloud-to-cloud procedure was applied for data integration. Following the alignment process, the datasets were fully overlapped as seen in Figure 6, enabling a visual assessment of their spatial overlaps. To verify the reliability of cloud-to-cloud registration, a systematic visual inspection was performed using both horizontal and vertical sections. Transition areas where inconsistencies such as gaps and wall intersections were most likely to occur were checked. The inspection confirmed a satisfactory spatial correspondence between the datasets, and no significant anomalies or discrepancies were observed that could compromise the subsequent modelling stages.

The geometric accuracy of the photogrammetric model was assessed using RMS reprojection error statistics obtained after camera optimization in Agisoft Metashape resulting in a mean reprojection error of 0.76 pixels, which indicates a high level of internal geometric consistency between image observations and the estimated camera parameters. Reprojection error values below one pixel are widely regarded as suitable for metric analysis and as an indicator of bundle adjustment quality and geometric reliability in SFM-based reconstructions (Knuth et al., 2023). In addition, the external metric accuracy of the model was evaluated through a model-space Root Mean Square (RMS) error analysis based on two independent control markers with known real-world distances; comparison between the measured distance in the reconstructed model and the reference value yielded an RMS error of 0.017 m. These results suggest that the generated model provides a level of geometric accuracy that is appropriate for metric assessment within the scope of the present study.

The processed data are then imported into the HBIM environment, where semantic enrichment is applied. Material typologies, deterioration patterns (cracks, deformations, biological growth), ornaments, and non-original intervention layers are identified.

Figure 6. Overlapped point cloud of the Ayakapi Hammam generated through UAV and 360° panoramic camera scans.

3.3 Scan-to-HBIM model

The transfer and interpretation of the scanned data representing the current state of the structure into the HBIM environment (Scan-to-HBIM) were conducted using photogrammetric datasets to ensure a consistent and reliable basis for geometric documentation. The resulting 3D photogrammetric model served as the primary geometric reference for the development of the HBIM model.

The point cloud obtained from photogrammetric scanning was not directly converted into a surface or solid model; instead, architectural components were modeled in an Autodesk Revit environment based on parameters using the point cloud as a reference. This approach enables for the integration of semantic information about the structure into the model, rather than just a geometric representation. Consequently, structural elements are defined not only by their dimensional accuracy but also enriched with historical, structural, and material attributes.

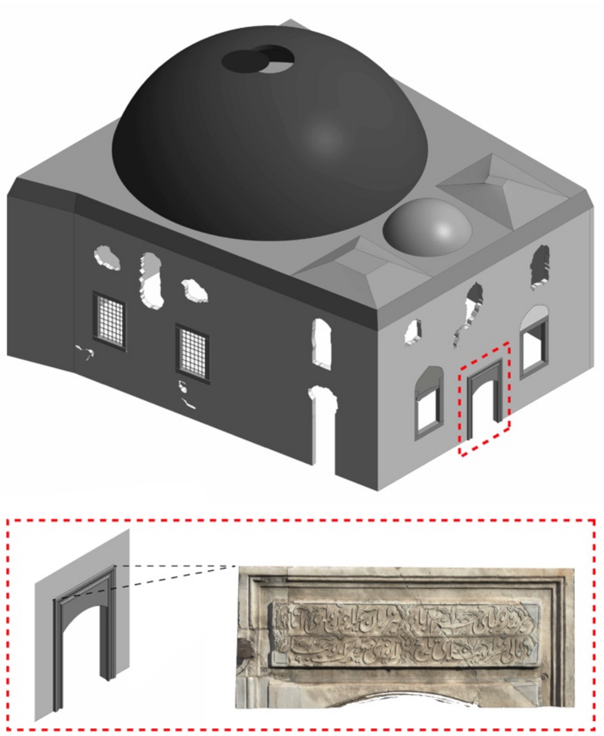
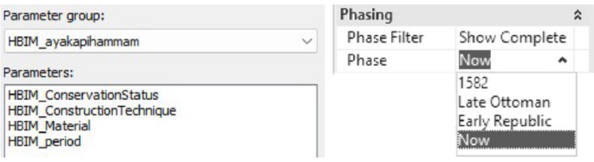


Figure 7. HBIM Model of Ayakapi Hammam and The Marble Inscription Stone Located The Original Entrance.

The scan-to-HBIM model representing the current state of the hammam was developed at the LOD 300 level, shown in Figure 7, where architectural elements are modeled with accurate geometry, spatial position, orientation, and dimensions based on measurement data. At this level, primary components such as walls, domes, vaults, and openings are explicitly defined as separate parametric objects, allowing for reliable interpretation of their forms, positions, and relationships within the model. In the same figure, the marble inscription stone at the original entrance was scnaned with LIDAR. The outcome data integrated into the HBIM environment as image-based parameter. Through the process, attributes such as material type, historical meaning and conservation state value were defined usign HBIM patameters.



(a) (b)

Figure 8. a) Shared Parameters of Families b) Phasing Scheme of Models.

A classification phase scheme was created to ensure the consistent and coherent representation of architectural elements within the HBIM model. Primary structural components such as walls, domes, and vaults are defined as distinct categories, separate from secondary elements including openings and period additions. Each category of structural element is associated with specific shared parameters (see Figure 8) where information such as construction technique, material, state of preservation, and period affiliation can be entered. The phasing tool was used to define different historical layers corresponding to significant historical periods, including the 16th century construction phase, subsequent Ottoman interventions, early Republican era alterations, and the current state. By assigning architectural elements to both specific parameters and phases, the model made it possible to obtain and visualize multiple interpretable states of the building without repeating the geometry.

3.4 Reverse reconstruction

The reverse reconstruction approach aims to geenrate a secondary HBIM model representing the architectural condition the hammam might have reached had it undergone a natural aging process without any destructive interventions throughout its historical process. The model does not aim to recreate the idealized or original state exactly (as a restoration proposal); rather, it presents a reasonable and controlled interpretation based on typological, structural, and material based evidence.

The reverse reconstruction model (see Figure 9) was developed by integrating the 16th century LOD 100 model obtained from relatively well-preserved Ottoman hammams sharing comparable plan typologies, structural systems, and construction techniques- using the direct scan-to-HBIM model representing the current condition of the structure. These two reference models were jointly used to assess missing, altered or deteriorated architectural elements and to guide interpretative decisions regarding their plausible historical configurations.

Point cloud obtained through photogrammetry was used as a visual and proportional reference. In order to verify dimensions, and overall massing consistency, the point cloud was selectively overlaid onto the base HBIM geometry within the Adobe Photoshop environment, deliberately avoiding a full mesh-based reconstruction. This point cloud superposition process ensured that the model remained parametric and information-driven while maintaining consistency with the documented physical condition. Material degradation and aging effects were limited throughout the model. To show long-term environmental exposure and weathering, minor surface-level visual interventions, such as cleaning of surface and some infill were applied without generating explicit decay or damage patterns.

Throughout the reverse reconstruction process, the effects of late additions, incompatible repairs, and irregular deformations due to disuse have been minimized, moreover the vegetation over the dome has been cleaned. However, traces of long-term use, material weathering and age-related transformation have not been completely eliminated. Thus, the model does not represent a “perfect” architectural condition, but a possible intermediate state within historical continuity.

Using parametric structural elements defined in the HBIM environment, partially collapsed vaults, deformed wall surfaces, or structural relationships that had lost their continuity and proportional integrity were re-evaluated. These interventions were not with intended to achive formal completeness or visual idealization. Instead, they were undertaken to clarify the hammam’s spatial organization, construction logic, and structural system. In this sense, reverse reconstruction is used as an analytical approach to support architectural understanding rather than as a restoration proposal.

Figure 9. Reverse Reconstruction Model of the Ayakapi Hammam.

4. Results and discussion

The comparative reading of the three HBIM-based models- the hypothesized sixteenth century configuration, the present condition derived from scan-to-HBIM data, and the reverse reconstruction model- provides a structured framework for interpreting architectural continuity, loss and uncertainty in the Ayakapi Hammam.

In the 16th. century model, the architectural composition is expressed through a coherent volumetric arrangement, where domed spaces, arches, and enclosing walls define a legible and continuous spatial system. The smooth and uninterrupted surfaces of the domes and walls reflect an interpretive representation of structural completeness and spatial clarity, serving as a reference model for understanding the original architectural logic rather than as a definitive historical reconstruction.

A key limitation identified in this study concerns the high degree of uncertainty associated with the sixteenth-century model, primarily due to the limited historical sources. The partial collapse of the structure over time, for reasons that remain largely undocumented, has significantly constrained the amount of reliable physical and material evidence available for interpretation. Analysis of the 1960 aerial photograph (see Figure 3) indicates that the caldarium and praefurnium parts of the structure was still standing at that time; however, the causes of its subsequent collapse over the past 65 years, as well as the processes through which its materials were lost or removed, remain unknown. Oral history interviews conducted within the surrounding neighborhood did not provide verifiable or consistent information to clarify these processes. Consequently, even the surviving portions of the Ayakapi Hammam reveal substantial information gaps when subjected to the reverse reconstruction process, underscoring the interpretative nature of the proposed model and highlighting its dependence on the quality, continuity, and resolution of both archival and material data.

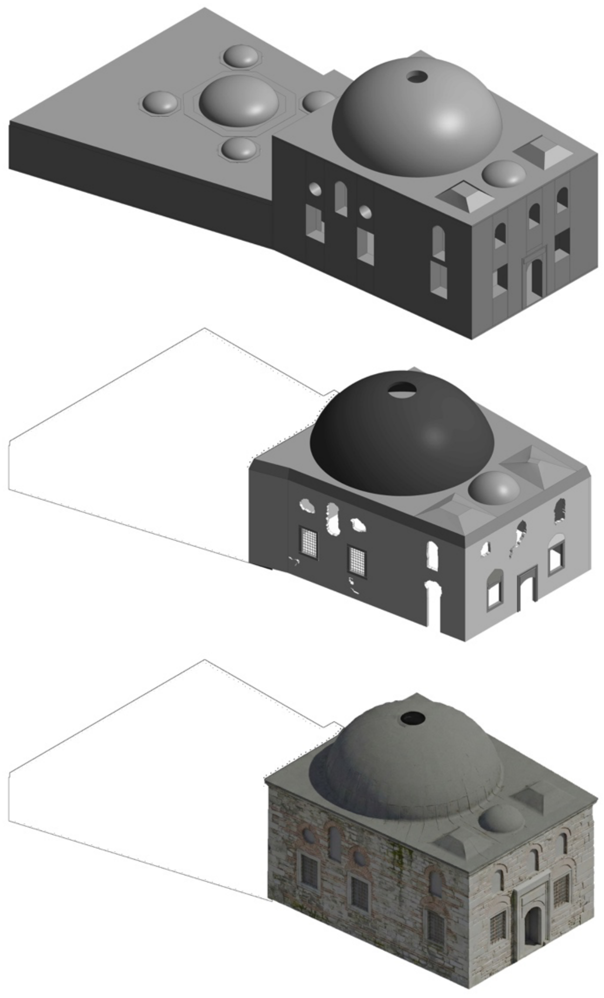


Figure 10. Three HBIM models respectively the sixteenth century model, scan-to-HBIM model current situation, reverse reconstruction model.

The scan-to-HBIM model of the present condition demonstrates a markedly different architectural state. While the primary massing and the main dome remain identifiable, the model reveals significant surface degradation, material loss, and partial collapse, particularly along wall elevations and opening edges. Figure 10 illustrates that penings appear fragmented or deformed, and surface irregularities indicate long-term exposure and deterioration. These visual characteristics directly reflect the limits of the recorded data and make visible the uneven preservation of architectural elements. The scan-to-HBIM model therefore functions as both a geometric record and a diagnostic representation of damage and aging.

The reverse reconstruction model mediates between these two conditions by reinterpreting missing or damaged architectural elements while retaining evidence of material aging. Compared to the sixteenth-century model, the reverse reconstruction does not present smooth or idealized surfaces; instead, textures, material articulation, and subtle irregularities are maintained to reflect a non-pristine condition. In contrast to the scan-to-HBIM model, architectural elements such as openings, wall surfaces, and domed forms are spatially re-integrated, allowing the overall architectural composition to be read more coherently. This visual balance between continuity and imperfection distinguishes the reverse reconstruction model as an interpretive rather than restorative representation.

5. Conclusion

In this paper, a novel methodological framework, reverse reconstruction, is proposed. The method integrates semantic information derived from historical photographs, drawings, archival documents, theses, and narrative sources with photogrammetric models of the hammam's current state, translating this combined dataset into an HBIM environment. Through this process, the study explores a hypothetical architectural evolution of the Ayakapi Hammam, assuming a natural aging trajectory consistent with conservation principles and the absence of destructive interventions. Although the methodology is demonstrated through the specific case of the Ayakapi Hammam, it suggests a transferable and adaptable framework that may be applied to other heritage structures as an exploratory tool for analyzing architectural evolution and conservation-informed aging processes. The outcomes should be regarded as preliminary results, intended to test the methodological potential of reverse construction rather than to assert a definitive historical or restorative model.

In the case of the Ayakapi Hammam, the building has been particularly vulnerable to neglect and transformation, as it remained in private ownership and was not transferred to a vakıf structure, resulting in prolonged exposure to deterioration and limited conservation oversight. Despite being frequently referenced in the literature, available information on this Sinan-era structure remains fragmented and relatively scarce. Therefore, the reverse construction methodology not only functions as an analytical tool but also indicates potential future applications in participatory and inclusive conservation practices. By enabling the integration of HBIM-based models with immersive visualization technologies such as virtual and augmented reality (VR/AR), the proposed approach may support broader social inclusion in decision-making processes related to restoration and preservation activities. Moreover, by making underlying historical assumptions, material evidence, and interpretative choices explicit, the method has the potential to contribute to a more transparent and critical engagement with the concept of authenticity in heritage conservation. Such applications could facilitate the communication of alternative conservation scenarios to non-expert stakeholders, thereby contributing to a more transparent and informed dialogue on the cultural value and future of historic buildings.

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