

Article

A Geospatially Enabled HBIM–GIS Framework for Sustainable Documentation and Conservation of Heritage Buildings

Basema Qasim Derhem Dammag^{1,2}, Dai Jian¹, Abdulkarem Qasem Dammag^{2,3}, Sultan Almutery⁴ , Amer Habibullah⁵  and Ahmad Baik^{6,*} 

¹ College of Architecture & Urban Planning, Beijing University of Technology, Beijing 100124, China; bassmadammag@emails.bjut.edu.cn (B.Q.D.D.)

² College of Engineering and Architecture, Ibb University, Ibb 910101, Yemen

³ College of Architecture and Urban Planning, Tongji University, Shanghai 200092, China

⁴ College of Cultural Heritage and Museology, The Royal Institute of Traditional Arts (Wrth), Riyadh 12632, Saudi Arabia

⁵ Department of Landscape Architecture, Faculty of Architecture and Planning, King Abdulaziz University, Jeddah 21589, Saudi Arabia

⁶ Geomatics Department, Architecture and Planning Faculty, King Abdulaziz University, Jeddah 21589, Saudi Arabia

* Correspondence: abaik@kau.edu.sa; Tel.: +966-05-056-63599

Abstract

Heritage buildings pose persistent challenges for documentation and conservation due to their geometric complexity, material heterogeneity, and the fragmentation of spatial and semantic datasets. To address these limitations, this study proposes a geospatially enabled HBIM–GIS framework that integrates hybrid photogrammetric survey data with semantic modeling and spatial analysis to support evidence-based conservation planning. A multi-source acquisition strategy combining terrestrial digital photogrammetry (TDP), Unmanned aerial vehicle digital photogrammetry (UAVDP), and spherical photogrammetry (SP) was employed to capture accurate geometric and semantic information across multiple spatial scales. Staged point-cloud fusion (UAVDP → TDP via ICP; SP → UAV–TDP via SICP) generated a high-density, georeferenced composite, achieving RMS residuals below 0.013 m and resulting in an integrated dataset exceeding 360 million points. From this composite, authoritative 2D drawings and a reality-based 3D HBIM model were developed, while GIS thematic mapping translated heterogeneous observations into structured, queryable layers representing materials, cracks, detachments, deformations, and construction phases. The proposed framework enabled the spatial diagnosis of deterioration mechanisms, revealing moisture-driven decay from plinth to mid-wall and concentrated cracking at openings and architectural transitions; side-to-side cracks accounted for approximately 55% and 65% of mapped fissures on the most affected façades. By embedding these diagnostics as element-level attributes within the HBIM environment, the framework supports precise localization, quantification, and prioritization of conservation interventions, ensuring material-compatible and location-specific decision making. The applicability of the framework is demonstrated through its implementation on a complex historic mosque in Yemen, validating its robustness under constrained access and resource-limited conditions. Overall, the study demonstrates that geospatially integrated HBIM–GIS workflows provide a reproducible, scalable, and transferable solution for the sustainable documentation and conservation of heritage buildings, supporting long-term monitoring and informed management of cultural heritage assets worldwide.



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Keywords: HBIM–GIS integration; UAV photogrammetry; terrestrial photogrammetry; GIS thematic mapping; cultural heritage conservation; 3D heritage modeling

1. Introduction

Cultural heritage (CH) is a multifaceted concept encompassing both tangible and intangible elements. The tangible aspects include physical items such as structures, monuments, and archeological sites, which serve as indicators of historical and cultural evolution, contributing to community identity and pride. They link individuals to their history and foster a sense of belonging in an increasingly dynamic environment [1,2]. Moreover, CH has significant economic value, especially through tourism, as heritage sites attract visitors and contribute to economic sustainability [3]. However, CH faces numerous threats, such as environmental degradation, urbanization, neglect, and the impacts of conflict, necessitating adaptive strategies to preserve its value for future generations [4]. Among the cultural heritage assets, heritage buildings (HBs) are particularly vulnerable. These buildings embody a succession of transformations over time, reflecting the dynamic nature of their cultural and historical contexts [5]. The materials, construction techniques, and pathological processes associated with HBs make them significantly different from modern structures [6]. Vulnerable materials, outdated systems, and inadequate documentation render these buildings susceptible to natural disasters, climate change, and human neglect [7]. Additionally, improper repairs without prior documentation compromise the historical and cultural significance of these structures [5,8,9]. It is essential to recognize that HBs are not static entities; rather, they represent evolving cultural and urban identities [5,10]. Consequently, sustainable conservation approaches, supported by advanced technologies, are crucial to understanding the historical, socio-economic, and technological contexts of these structures and ensuring their accurate documentation [9,10]. Advanced digital surveying methods, including terrestrial digital photogrammetry (TDP), unmanned aerial vehicle digital photogrammetry (UAVDP), and spherical photogrammetry (SP), have become indispensable in CH conservation. These technologies enable the accurate creation of three-dimensional models that capture intricate details and geometries [11]. TDP is known for its efficiency and affordability in obtaining detailed 3D data [12], while UAVDP covers large areas effectively, making it ideal for complex sites [13]. Additionally, SP has proven valuable for recording detailed forms, such as sculptures and architectural ornaments [14,15]. The integration of these photogrammetric approaches allows the generation of high-quality 3D models that serve as visual archives and assist in planning restorations [16,17].

Building on these advancements, geographic information systems (GIS) and Building Information Modeling (BIM) have become crucial tools for HB documentation and conservation. GIS supports the development of thematic maps that illustrate material distributions, deterioration patterns, and structural vulnerabilities, providing insights into conservation needs [18]. On the other hand, Heritage Building Information Modeling (HBIM) extends BIM applications to historic buildings by integrating historical, material, and structural data into parametric 3D models, facilitating their thorough documentation and management [19]. HBIM, which emerged in the late 2000s, has evolved into a digital methodology for managing the lifecycle of HBs, including conservation, refurbishment, and retrofitting [20,21]. HBIM merges building data, such as materials and construction techniques, with survey data to produce complex 3D models that reflect architectural, historical, and construction typologies [21–23]. It transforms this data into parametric models and libraries designed for CH, allowing the management of heritage components within

a unified software framework [24,25]. Additionally, HBIM improves decision making by offering virtual tours, making it an all-encompassing solution for understanding and conserving HBs [26,27].

Despite the substantial progress in GIS and HBIM technologies for HB conservation, critical gaps remain, particularly in resource-constrained and conflict-affected areas, such as Yemen [28]. While international studies have demonstrated the effectiveness of these technologies in stable environments, their application in areas with political instability, poor infrastructure, and limited historical records has been insufficiently explored [29]. Much of the current research focuses on well-documented, globally recognized HBs, neglecting significant, yet underrepresented, places like the Great Mosque in Ibb, Yemen. Moreover, there is a lack of established workflows for integrating diverse data sources, such as photogrammetry outputs, non-destructive testing results, and historical archives, into GIS-HBIM frameworks. This methodological weakness leads to challenges in replicating workflows, dealing with heterogeneous and inconsistent data, and translating findings into actionable conservation decisions. In Yemen, these challenges are compounded by the absence of coordinated heritage information systems at the national and local levels, limited institutional capacity, and demographic and land use pressures that accelerate the degradation of historic urban fabrics. The city of Ibb, recognized as Yemen's tourism hub, has experienced rapid deterioration and the stress of displacement, further endangering its landmarks, including the Great Mosque.

In response, this study aims to leverage the integration of GIS and HBIM to document and conserve the Great Mosque in Ibb, Yemen. The objectives are to: (1) employ hybrid technologies (TDP, UAVDP, SP) for accurate 3D surveying; (2) develop an architectural object library and create an HBIM model enriched with historical, material, and structural data; (3) use GIS to generate thematic maps for analyzing structural deterioration, including cracks and decay; and (4) enhance HBIM interoperability by integrating 2D GIS data for structural assessment and monitoring. By addressing these gaps, the study not only seeks to conserve the Great Mosque but also contributes to broader discussions on CH conservation, offering a replicable methodology for managing and conserving HBs in resource-constrained and conflict-affected regions. The combined use of GIS and HBIM provides a scalable framework for heritage management applications, supporting monitoring, maintenance planning, and risk-informed interventions while also improving the effectiveness of conservation efforts in challenging operational environments.

2. Related Works

In HB conservation, effective methods for documentation, management, and maintenance are essential. HBIM has emerged as a pivotal technology due to its ability to integrate detailed information within a 3D digital model, enhancing conservation efforts' accuracy, efficiency, and sustainability. Pioneering research, such as that by Oreni et al. (2013) [22], highlighted its significance in conservation. Angeloni et al. (2023) [30] also examined HBIM's role in architectural heritage conservation using automated 3D modeling integrated with industrial foundation class (IFC). Additionally, Murphy et al. (2021) [31] demonstrated HBIM's applicability in documenting Irish HBs' conditions, facilitating informed decision making on their conservation through BIM and laser scanning. Further contributions, like those from Oreni et al. (2014) [32] and Megahed (2015) [33], explored HBIM's role in the management and theoretical frameworks for HBs, employing simplified parametric models and integration of diverse data types. Khodeir et al. (2016) [34] focused on the sustainable retrofitting of Egyptian HBs using HBIM to evaluate conditions and identify opportunities for intervention. Several other works, including those by Martinelli et al. (2022) [35] and Baik and Boehm (2015) [36], have explored HBIM's application for

documenting and simulating construction systems in HBs. Barazzetti et al. (2015) [37] introduced semi-automated methods to generate parametric components from point clouds (PCs), integrating photogrammetry with laser scanning to enhance BIM-based documentation. Additionally, the integration of GIS with HBIM has significantly advanced HB management by enhancing spatial data analysis in conservation efforts. Zhang and Zou (2022) [38] emphasized that GIS–HBIM integration improves spatial mapping and degradation visualization, facilitating targeted conservation solutions. Chen et al. (2023) [1] used GIS to generate thematic maps linking spatial and semantic data, enhancing HBIM models for better decision making. Other studies, such as those by Tsilimantou et al. (2020) [39] and Themistocleous et al. (2022) [40], further explored GIS’s role in enhancing HBIM by integrating photogrammetric surveys and creating high-resolution maps for monitoring degradation. Brumana et al. (2018) [41] and Banfi (2016) [42] presented methodologies for developing HBIM libraries and dynamic parametric modeling, emphasizing detailed representation of construction elements. Almainani and Nawari (2016) [43] contributed by creating 3D BIM libraries for Islamic architecture, enhancing the understanding and preservation of heritage. While HBIM has been widely employed in Western nations for notable HBs, its application in resource-constrained and conflict-affected regions remains underexplored. Several studies, such as Taileb et al. (2023) [21] and Themistocleous et al. (2015) [44], used HBIM to generate high-resolution images for HBs, aiding in documentation and restoration planning. Dammag et al. (2025) [29] applied HBIM in reconstructing Ibb’s Big Gate and adjacent walls, identifying decay phenomena and guiding conservation efforts. Similarly, Liberotti et al. (2023) [45] demonstrated how the integration of algorithmic modeling with HBIM enables high-detail parametric representation of complex masonry vaults.

Despite these advancements, a gap exists in integrating GIS–HBIM workflows for conflict-affected regions, where access to historical data and technological resources is limited. The integration of multiple data sources, such as UAV and TDP with historical archives, is crucial for developing replicable workflows that can overcome these challenges. Overall, the literature supports the integration of GIS–HBIM as a robust, information-rich framework for HB documentation and conservation planning, but more research is needed to adapt it to resource-limited and conflict-impacted areas.

3. Materials and Methods

3.1. Overview of the Study Area

The Great Mosque of Ibb, also known as the ‘Umar Caliph/Omri Mosque, stands as a significant emblem of religious scholarship and heritage building (HB) development in the city. Local tradition attributes its construction to the caliphate of ‘Umar ibn al-Khaṭṭāb (r. 634–644 C.E.), with its establishment dated to approximately 643 C.E., making it one of the earliest Islamic religious edifices in Yemen [28]. Situated on a hill in the city center, the mosque is surrounded by residential structures to the north and west, with significant areas like Bab al-Nasr, As-maa School, and Al-Maj’ara to the south [46] (Figure 1).

Architecturally, the mosque is a single-story rectangular structure covering approximately 2440 m², featuring three entrances on the west and a fourth on the south that provides direct access to the prayer hall [47]. A canopied, domed portico, supported by two corner domes, facilitates entry and extends through a semi-circular vault towards the street on both the south and north, flanked by two western arches. An arcaded colonnade surrounds the exterior courtyard, creating a square court and ceremonial approach [48] (Figure 2). The architectural plan illustrates the mosque’s design through two primary components (Figure 3): (a) the main structure, encompassing its spatial and functional elements that define its religious and cultural identity (summarized in Table A1

(Appendix A)); and (b) architectural elements that embody the interplay of form, function, and symbolism inherent in Yemeni Islamic architecture (summarized in Table A2 (Appendix B)).

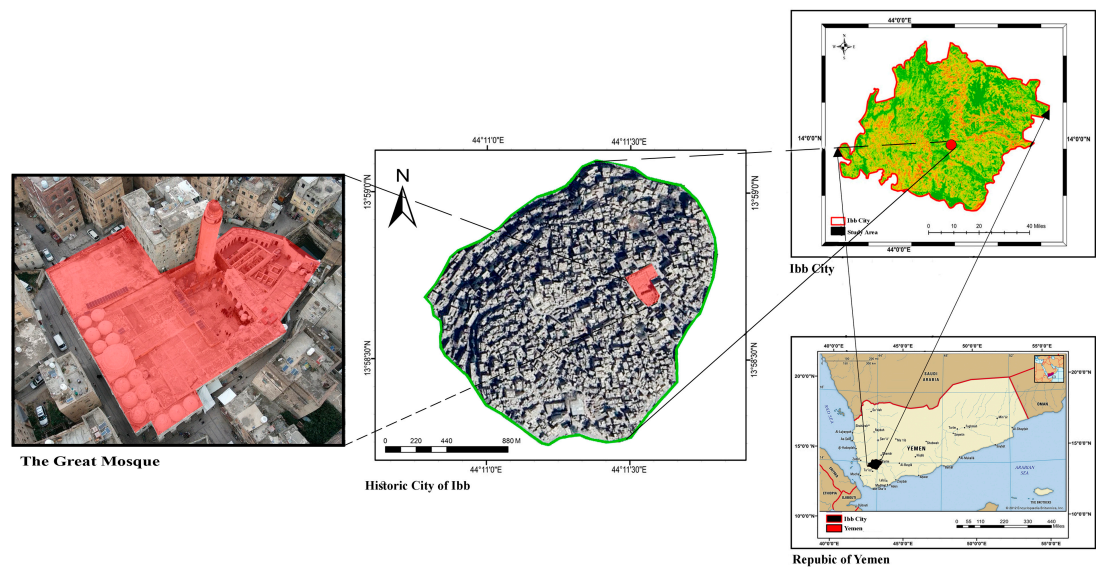


Figure 1. Location map of the study area.

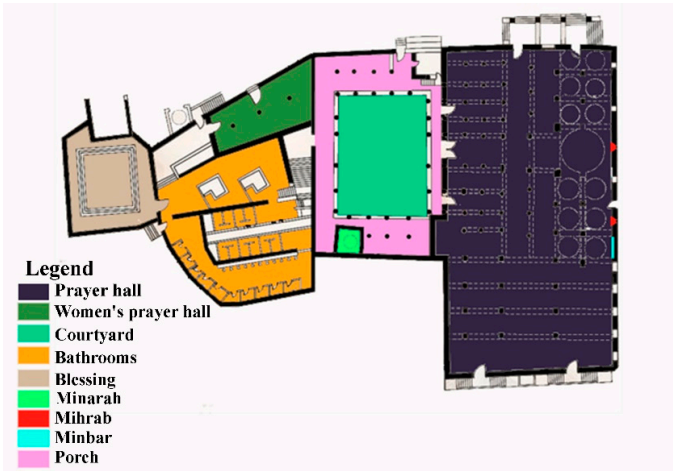


Figure 2. Architectural plan of the mosque.

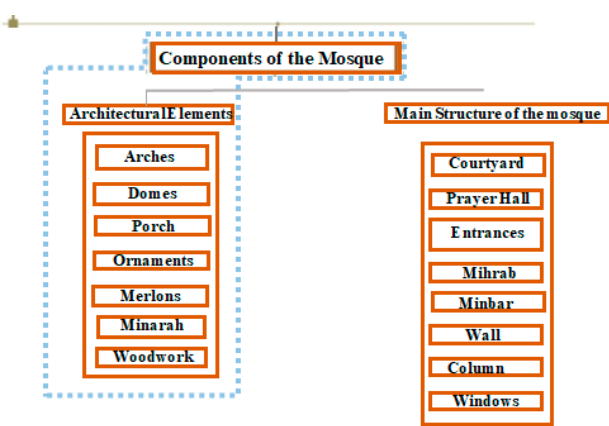


Figure 3. Components of the mosque in Ibb.

Structurally, continuous load-bearing masonry walls, made from locally sourced stone and limestone, provide global stability (Figure 4). These walls are finished with al-Qdad, a traditional composite of limestone and small stone spheres, used for both structural and esthetic purposes [49]. Clay infill enhances thermal performance, while timber is employed in doors, beams, and ornamental carpentry. Flat, multi-tiered roofing separated into square bays produces coffered ceilings adorned with engraved geometric and floral patterns [29] (Figure 5).

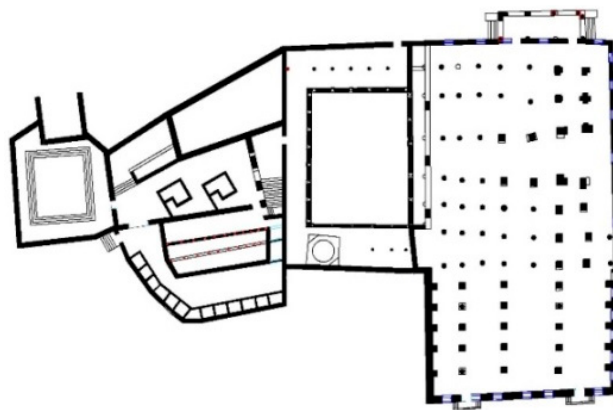


Figure 4. Structural framework of the mosque.

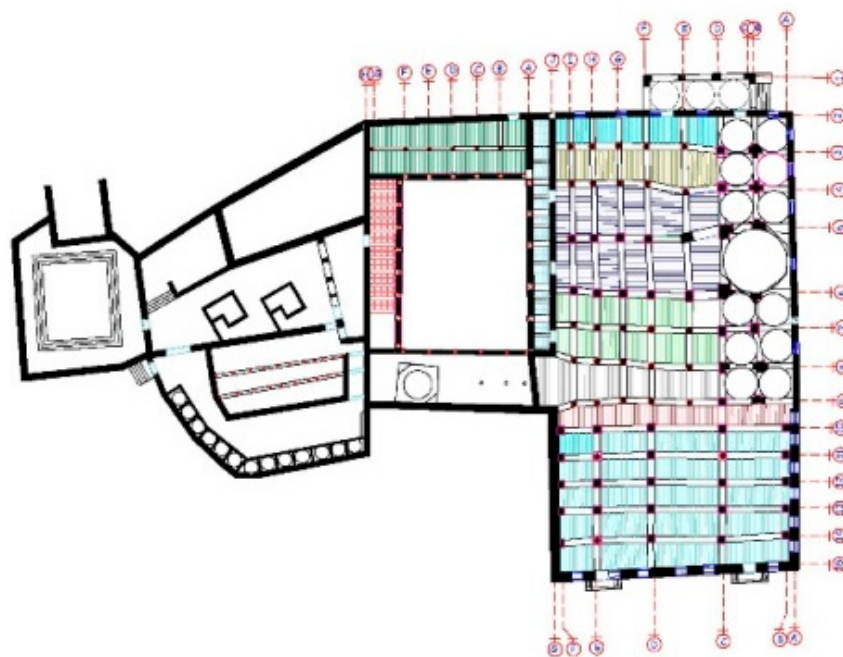


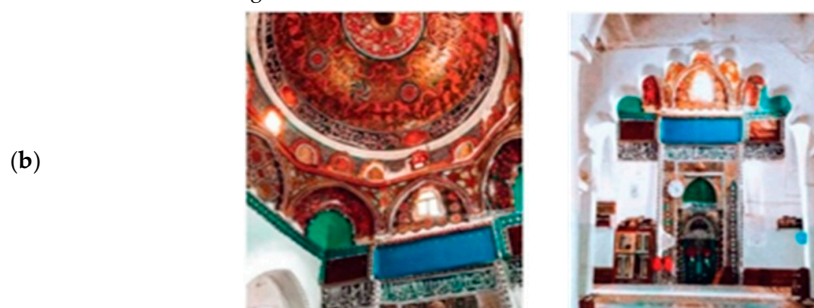
Figure 5. Ceiling plan showing coffered layout and engraved decorative motifs.

Materially, the mosque has experienced significant deterioration, affecting both its architectural integrity and visual clarity [48,50] (Figure 6). Initially, substantial layers of white gypsum were applied to intricately decorated surfaces, obscuring the original carvings and painted designs; much of the previous magnificence is now visible only where the plaster has deteriorated (Figure 6a). Modern painting techniques have altered the coloration of domes and ceilings, while overpainting of Qur'anic inscriptions has obscured important epigraphic details, reducing their historical significance (Figure 6b). Inadequate supervision of a 2007 intervention, involving the removal of support beams, led to a partial ceiling collapse [51] (Figure 6c). Further renovations in 2014 compromised authenticity: the historic wooden roof was replaced with contemporary materials,

the domes were repainted with synthetic pigments, and the minbar, previously adorned with Qur'anic and geometric carvings, was extensively overpainted, obscuring its original craftsmanship. Similarly, the minaret, which was coated with white plaster in 2015, collapsed on 31 October 2015; the 2018 rebuild restored its vertical shape but did not replicate the original design or craftsmanship [46] (Figure 6d).



The deterioration of interior architectural arches over time, showcasing the fragility of intricate ornamental detailing



The gradual deterioration of the mihrab and dome, highlighting the loss of intricate details and vibrant colors.



The deterioration in the interior ceiling, with visible signs of decay affecting both the structural integrity and ornamental details.

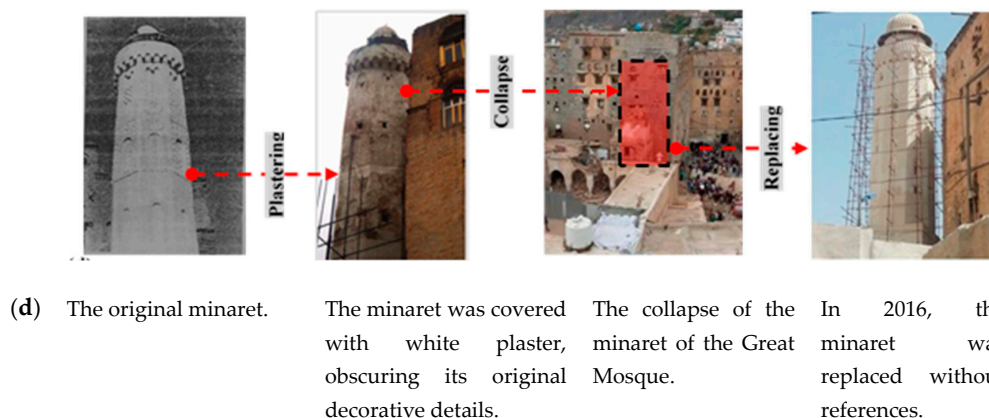


Figure 6. Challenges faced by the mosque in terms of deterioration and maintenance.

The Great Mosque of Ibb, while a significant cultural and architectural landmark, also faces the unique challenges of being situated in a conflict-affected region, where access to resources and historical records is limited. This context makes the integration of advanced technologies like UAVDP, TDP, and SP essential for precise documentation, as traditional methods may not be feasible or reliable. The data collection process outlined in this study demonstrates how advanced surveying methods can be adapted for use in areas with limited infrastructure and political instability, offering a replicable model for similar sites.

3.2. General Methodological Approach

This study employs a hybrid approach that integrates advanced surveying technologies, GIS, and HBIM for the conservation of the historically significant Great Mosque of Ibb. In this study, the term “digital model” refers to the initial reality-based outputs derived from photogrammetric processing (e.g., PCs and surface meshes). The term “geometric model” denotes the purely spatial and metric representation of architectural elements, while the “HBIM model” refers to the enriched parametric model in which geometry is integrated with semantic, historical, and material information. The methodology ensures precise and sustainable conservation by combining terrestrial digital photogrammetry (TDP), unmanned aerial vehicle digital photogrammetry (UAVDP), and spherical photogrammetry (SP) to acquire high-resolution geometric and semantic data. These techniques provide detailed ground-level imagery, aerial perspectives of inaccessible areas such as the roof and minaret, as well as panoramic views of complex geometries including domes and arches. Historical data—comprising archival documents, historical records, architectural plans, and documentation of past restoration efforts—were collected from local official entities, including the Governorate Office, Endowments Office, and the General Authority of Antiquities and Museums (Figure 7a–d). These records form the foundation for documenting both the mosque’s physical and historical contexts.

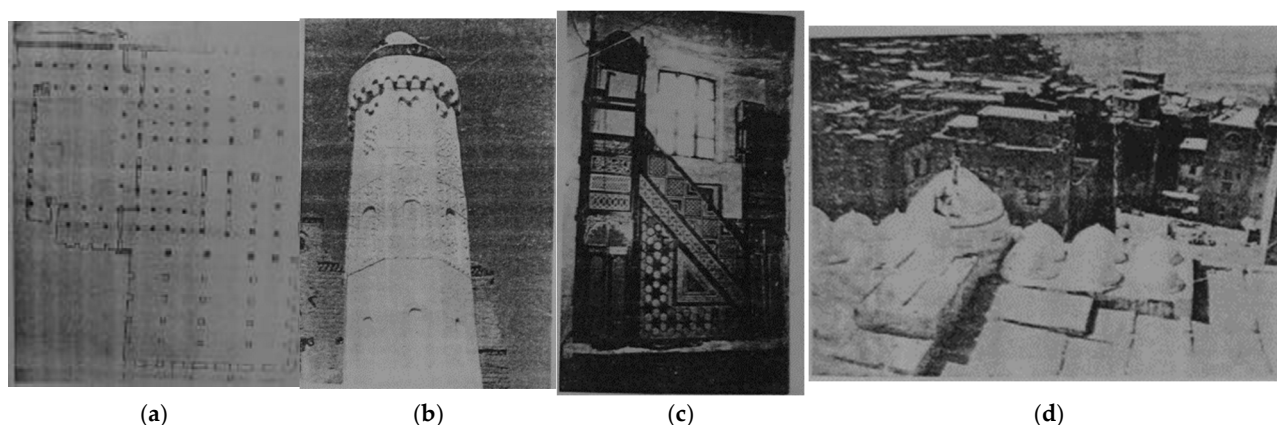


Figure 7. Historic drawings of the building. (a) Horizontal plan of the building. (b) Minaret of the mosque. (c) Minbar. (d) The main dome and side domes in the Qibla porch.

The workflow follows sequential steps to ensure accuracy and thoroughness. Initially, historical materials are reviewed to understand the mosque’s construction phases and previous modifications, reconciling discrepancies through archival blueprints, historical images, and field notes. A comprehensive 3D geomatics survey is then conducted using hybrid photogrammetry techniques to produce distinct PCs for various sections of the mosque. Camera calibration and image overlap ($\geq 60\%$) are meticulously designed, with ground control points (GCPs) established for scaling and georeferencing. The PCs are processed, filtered, and aligned using an iterative Closest Point (ICP)-based registration pipeline (with SICP for SP) to generate a cohesive 3D representation of the mosque’s

architectural and structural features. Outliers are removed prior to meshing or decimation, where required. GIS techniques are subsequently applied to generate thematic maps highlighting deterioration patterns such as cracks, erosion, and material degradation. These maps provide critical insights into structural vulnerabilities and are standardized to a common spatial reference to facilitate integration with HBIM elements.

In the subsequent phase, the processed geometric and spatial data are integrated into an HBIM framework through parametric modeling of architectural components, including minarets, domes, and arches. The resulting HBIM model is enriched with semantic information on materials, structural assessments, and deterioration diagnostics derived from GIS analysis. All segmentation, classification, and semantic enrichment steps are implemented through rule-based and expert-driven procedures rather than AI- or machine-learning-based automation. Semantic segmentation ensures accurate categorization of architectural elements, while ontology development links historical and material-specific information, enhancing understanding of the mosque's conservation status.

Although demonstrated through the case study of the Great Mosque of Ibb, the proposed hybrid workflow—integrating UAV-based, terrestrial, and spherical photogrammetry with GIS–HBIM—was intentionally designed to be adaptable to heritage sites in resource-constrained and conflict-affected contexts. In such environments, traditional documentation methods are often limited by restricted access, incomplete historical records, and constrained technical infrastructure. The proposed framework offers a flexible and resilient solution capable of operating under these constraints.

A key novelty of the study lies in the semantic embedding of building pathologies at the element level within the HBIM environment. Unlike conventional approaches that rely on descriptive inventories or isolated thematic maps, the workflow associates pathology observations—such as cracks, moisture-induced decay, detachments, and deformations—with individual architectural elements as parametric attributes. This element-level enrichment enables each HBIM component to carry condition-related information, including severity, spatial extent, provenance, and survey date, thereby supporting traceable diagnostics, quantitative assessment, and informed conservation decision making. By integrating GIS-based pathology mapping with HBIM semantics, the approach advances beyond geometric documentation toward an integrated diagnostics-to-action framework for heritage conservation (Figure 8).

3.2.1. Data Acquisition

Given the constraints of the site, it was challenging to obtain comprehensive CH data using a single method. Therefore, a hybrid surveying approach was employed, integrating three 3D surveying techniques: TDP, UAVDP, and SP. These techniques were selected for their ability to capture high-resolution data from difficult-to-reach areas and provide comprehensive geometric documentation.

The process was divided into three main phases:

1. Pre-survey stage: Research into surveying and mapping requirements → Development of a strategy → Adjustment and calibration of instruments → Preparation and briefing of survey personnel.
2. Survey stage: Position targets → Prepare instruments → Establish GCPs (used as common references across all datasets for alignment and measurement) → Acquire images → Finalize survey.
3. Post-survey phase: Pre-process point clouds (PCs) → Denoising → Merging and alignment → 3D parametric modeling → Final mosque model.

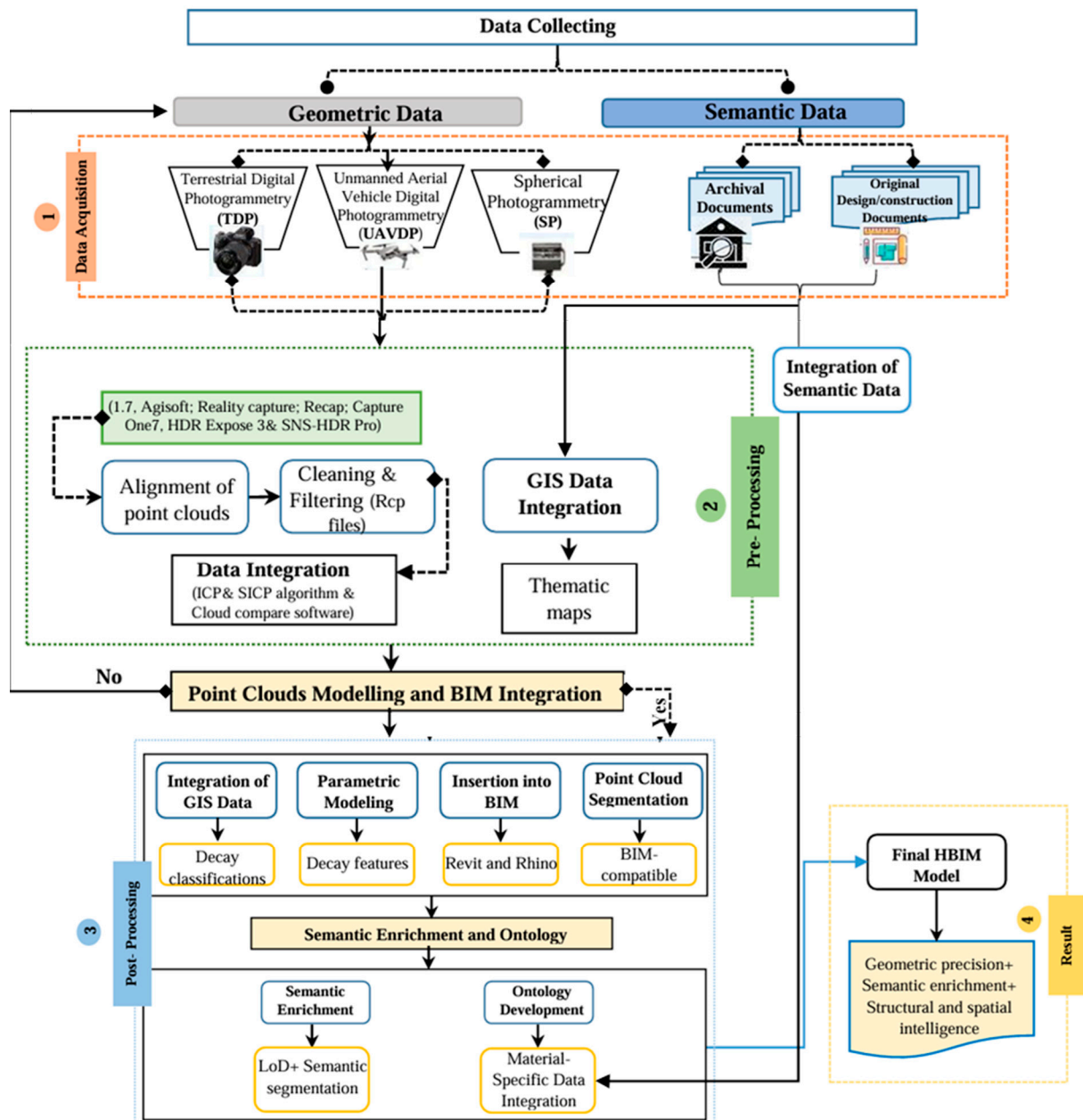


Figure 8. Proposed HBIM-GIS-AI workflow.

The operational workflow illustrating the integration of survey positions, image-based acquisition techniques (TDP, UAVDP, SP), and data-processing steps used in the hybrid documentation strategy is illustrated in Figure 9.

1. Unmanned Aerial Vehicle Digital Photogrammetry (UAVDP)

The UAVDP survey was conducted using a DJI Mavic 3 Classic camera (20 MP, 24 mm eq., ~84° FOV), ensuring stable image geometry and consistent radiometry across acquisitions. The survey was organized into four distinct flight types, each designed to capture different spatial dimensions of the mosque. The multi-flight strategy aimed to provide extensive coverage with high accuracy while minimizing data gaps.

- (1) Double-grid (nadir) flight: Captured the top view of the mosque and surrounding area with high geometric precision (Figure 10). Orthogonal cross-flights created a systematic grid and a highly overlapped, convergent image network, improving accuracy and robustness in photogrammetric processing. The camera was triggered

every 2 s, with speed tuned to maintain the specified 80%/60% overlaps, minimizing RMSE (especially horizontally) and strengthening model geometry. Approximately ~1000 images were acquired for subsequent processing.

- (2) Horizontal flight: Executed to capture exterior façades and the inner courtyard. The UAV followed the outer perimeter at >25 m AGL (above ground level), ensuring full-height coverage of façades, including the tallest elements. The camera was oriented horizontally (0° pitch) to acquire detailed elevation data that complements the prior nadir set. Approximately ~1500 images were collected for photogrammetric processing.
- (3) Oblique flight (~45°): Conducted to capture oblique imagery for edge detail and complete coverage of the mosque interior and all four courtyard façades. Flown at 30 m AGL, providing safe clearance above the ~25 m minaret for full vertical coverage. Camera tilt was ~45° to suppress horizon and shadow effects, as recommended for complex buildings and urban scenes [52]. Approximately ~950 images were acquired.
- (4) Helix flight (partial): Helix flight (partial): A fourth, specialized mission documented vertical elements, especially the minaret, with higher spatial accuracy via a partial helix: the UAV ascended in a semi-spiral, acquiring oblique images at multiple heights and angles (Figure 11). On-site constraints (the minaret's east side abuts a neighboring building with <0.5 m clearance) precluded a full 360°, so a ~270° arc (south–west–north) was flown at safe standoff; approximately ~250 images were acquired. Camera tilt (θ) was dynamically adjusted with altitude (h) to maintain façade focus and limit horizon distortion, as in Equation (1).

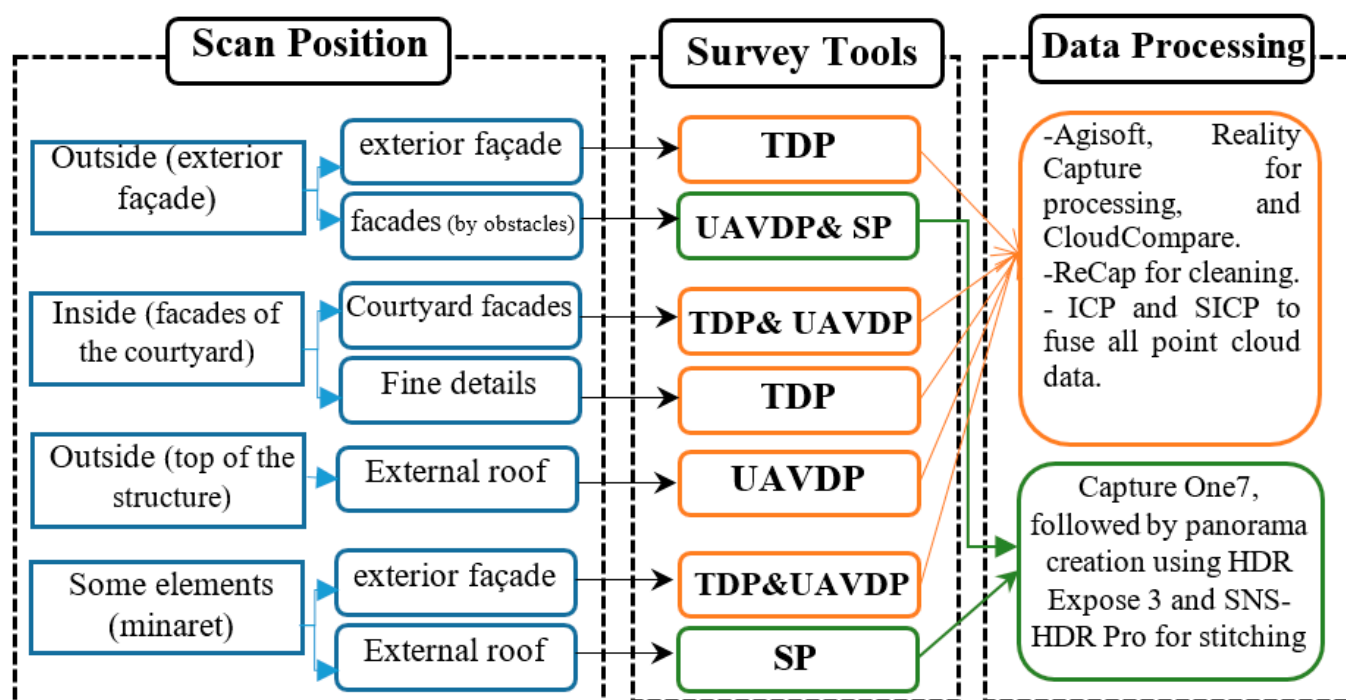


Figure 9. Workflow of the hybrid image-based survey.

$$\theta(h) = \frac{(\arctan(\text{MinaretRadius}))}{(\text{Flight Radius} - h \times \tan\alpha)} \quad (1)$$

where MinaretRadius and Flight Radius are measured in meters, and α is the longitudinal slope angle of the spiral flight path.

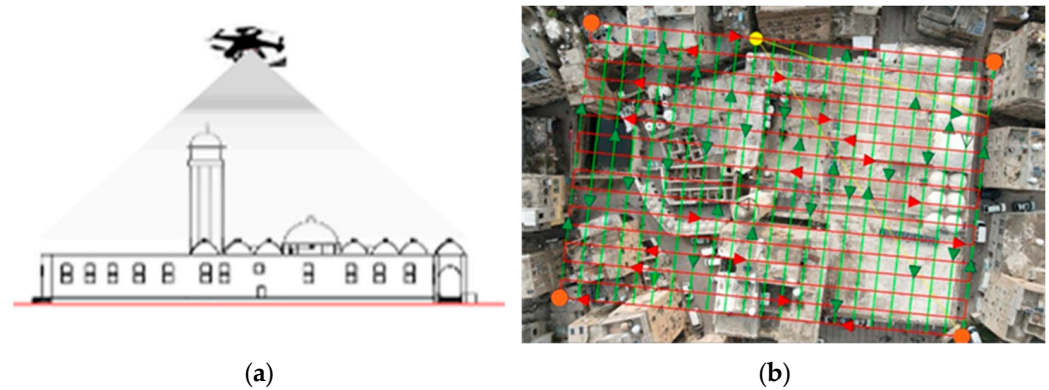


Figure 10. (a) A double-grid flight, (b) planning and execution of a double-grid flight.

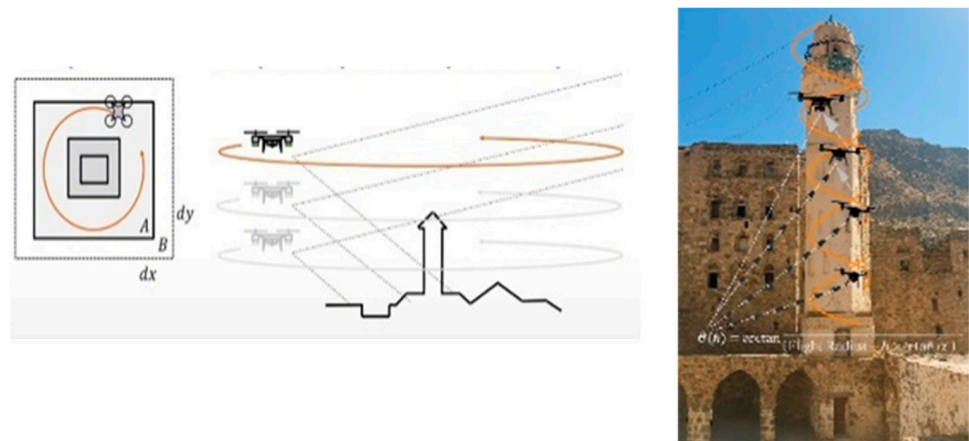


Figure 11. UAVDP helix flight (Partial) path around the minaret of the mosque.

2. Terrestrial digital photogrammetry (TDP)

TDP complemented UAV imagery in areas where higher resolution and controlled baselines were required. A Canon EOS 5D Mark II camera was used with a 35 mm focal length and 6048×4032 px resolution. This setup was chosen for its balance between field-of-view, ground resolution, and lens distortion, taking into account the spatial constraints posed by adjacent residential façades. Field-of-view (FOV) and Ground Sampling Distance (GSD) were calculated based on the camera specifications as shown in Equations (2) and (3).

$$\text{FOV}_{\text{horizontal/vertical}} = 2 \times \arctan\left(\frac{\text{Sensor Width/Height}}{2 \times \text{Focal Length}}\right) \quad (2)$$

$$\text{GSD} = \frac{\text{Sensor Width (mm)} \times \text{Flight Height (m)} \times 100}{\text{Focal Length (mm)} \times \text{Image Width (pixels)}} \quad (3)$$

where sensor width and sensor height are in mm; pixel size is in micrometers, distance to the subject is in meters, and focal length is in mm.

Methodologically, the survey was organized as follows:

(i) Facades and courtyards were segmented into horizontal and vertical tiers to respect line-of-sight limits.

(ii) Each segment was photographed in vertical or horizontal strips with $\geq 60\%$ overlap (Figure 12a) to ensure robust alignment.

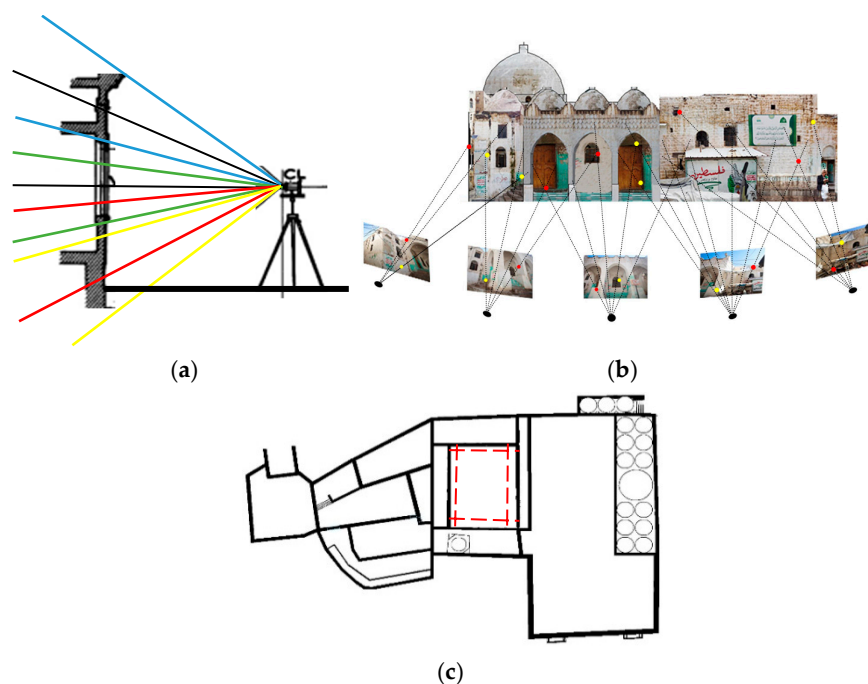


Figure 12. (a) An illustration of the process of dividing facades during photography and the percentage of overlap between images (60%) in both the vertical and horizontal directions. (b) Shooting positions of TDP for the case study. (c) Scale correction of TDP for the study.

(iii) A pre-survey cleaning was conducted to remove obstructions and ensure visibility of all architectural details such as corners of windows, doors, and walls.

(iv) Critical transitions (e.g., doors) were recorded both open and closed to maintain topological continuity between the exterior and the courtyard. In total, approximately 4000 terrestrial images were acquired, with camera stations and viewing orientations mapped in Figure 12b. To align the TDP model with the geodetic framework of the project (WGS 84/UTM Zone 38N), absolute scaling was applied using courtyard baseline distances (Figure 12c). The model was registered with the GCP-constrained optimization, ensuring its robust integration with UAV-derived datasets.

3. Spherical photogrammetry (SP)

SP was used to acquire close-range panoramas for areas with constrained stand-off and complex geometries, such as the concealed east face of the minaret and decorative bands, complementing the UAV and TDP datasets. A Canon EOS-1Ds Mark III (5616 × 3744 px) with a Sigma 15 mm f/2.8 lens was employed, mounted on a Manfrotto 808RC4 tripod with a Nodal Ninja 5R spherical head. The aperture was set to f/9 to balance depth of field and optical sharpness, ensuring high clarity across curved surfaces. Approximately 150 images were captured with the panorama tiling/coverage computed as shown in Equations (4) and (5).

$$P = \bigcup_i I_i = \text{InT}(I_i) \quad (4)$$

$$\text{FOV} = 2\pi \times \frac{H}{360^\circ} \times \frac{V}{180^\circ} \quad (5)$$

where P is the spherical panorama, I_i represents individual images, T is the transformation function, n is the number of images; FOV is the field of view, and H and V are the horizontal and vertical angles, respectively.

The acquisition followed a three-stage protocol:

(i) Overlapping Images: A series of overlapping images was captured to assemble full-sphere panoramas (360° horizontal, 180° vertical) of the areas of interest. This provided extensive coverage of complex structures.

(ii) Camera Movement: The camera was rotated along the yaw and pitch axes around the nodal point to achieve the necessary angular increments and overlap, ensuring high accuracy and coverage.

(iii) Lens Distortion Compensation: The images were corrected for lens distortion and then stitched together to create equirectangular panoramas. This process ensured that the resulting images were geometrically accurate for integration with other datasets.

(iv) The final stitched image sets were then integrated with the UAV and TDP networks using shared tie points and GCPs to ensure consistent scaling and orientation. This workflow delivered continuous, parallax-controlled coverage of tall and curved elements, filling visibility gaps in the building-scale documentation.

4. Ground control points (GCPs)

The use of GCPs was planned to enhance the absolute accuracy of photogrammetric datasets. A two-phase GCP strategy was employed: (i) in the first phase, 32 GCPs were distributed across the precinct and measured with a total station; 25 valid points were confirmed, comprising 15 control points (CPs) used for georeferencing and 10 check points (ChPs) for independent accuracy assessment (Figure 13a). (ii) In the second phase, additional control was set specifically for the TDP campaign: 20 valid points in total (14 CPs and 6 ChPs) (Figure 13b).



Figure 13. Distribution of GCPs (a) across the mosque during the UAVDP survey; (b) around the mosque during the TDP survey.

Proper spatial distribution in plan and height is essential when laying out GCPs, as noted by Chizhova et al. (2020) [53]; the absence of control at higher elevations can degrade model accuracy. Accordingly, and given limited ground space and restricted access around the mosque, several points were affixed directly to vertical walls or placed within the courtyard, ensuring visibility in both oblique UAV imagery and ground-based photographs. Georeferencing accuracy was evaluated on CPs and independently on ChPs using the root-mean-square error (RMSE) (Equations (6) and (7)).

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (\Delta_i)^2} \quad (6)$$

where Δ_i is the residual (estimated minus reference) for point i , and n is the number of points for each axis

$$\text{xRMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (\Delta X_i)^2}, \text{ yRMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (\Delta Y_i)^2}, \text{ zRMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (\Delta Z_i)^2} \quad (7)$$

Aggregates used in reporting:

$$\text{RMSE}_{XY} = \sqrt{(\text{xRMSE})^2 + (\text{yRMSE})^2}, \text{RMSE}_{3D} = \sqrt{(\text{xRMSE})^2 + (\text{yRMSE})^2 + (\text{zRMSE})^2}$$

The variation in number, placement, and spatial distribution of GCPs and ChPs between the UAV and TDP campaigns was intentional, reflecting each method's spatial requirements. All observations were referenced to a unified coordinate reference system (CRS), WGS 84/UTM Zone 38N, ensuring seamless integration during processing and calibration.

5. Building Materials' Characterization

Characterizing and classifying building materials is a crucial step in developing an integrated information system for HBs. This phase is fundamental for assessing the conservation status of the structure, documenting the types of construction materials, and mapping degradation patterns on architectural surfaces. The categorization of building materials, coupled with the examination of decay patterns, provides a deeper understanding of the building's pathology, ultimately assisting in managing the progression of its degradation [54,55]. To achieve this, preliminary in situ characterization and deterioration assessment were carried out using accessible, simple procedures suitable for the given resources. The evaluation process began with traditional visual inspection (TVI) as an initial field assessment, which facilitated the identification of observable structural deficiencies such as fissures, discoloration, and surface degradation. Close-range photogrammetry (CRP) was then employed to capture these conditions meticulously, documenting textures, hues, and visible damage for further analysis. For a more comprehensive perspective, UAV imaging using the DJI Mavic 3 Classic was deployed, providing an elevated viewpoint to assess degradation and structural vulnerabilities on the mosque's façade. Additionally, AI-enhanced image analytics (e.g., DroneDeploy and orthomosaic mapping using RGB imagery) were integrated with the UAV imagery to improve the analysis, yielding multifaceted insights into material states, including moisture levels and material degradation. This approach successfully detected hidden moisture pockets and indicators of erosion in otherwise inaccessible locations by integrating UAV-derived products with CRP documentation [56].

To gain a deeper understanding of material integrity, tests on surface hardness and texture were performed using basic equipment to evaluate surface resistance and uniformity, identifying regions more vulnerable to erosion and other types of degradation. Moisture analysis was conducted using basic humidity sensors to assess interior moisture levels within the walls, thus delineating regions susceptible to dampness and degradation. While these procedures lack the depth of advanced diagnostic instruments, they establish a solid foundation for comprehending the building's current condition. The integration of visual inspection, close-range photography, AI-enhanced UAV imaging, and surface testing provided a comprehensive assessment of the mosque's material composition and structural integrity. This holistic approach enhances our understanding of the causes of deterioration and facilitates focused conservation planning, ultimately aiding in the successful management of further degradation.

3.2.2. Data Processing

The point data acquired from different measurement methods required independent pre-processing for each method separately, to form the PC for each method through different software due to their different characteristics. Consequently, the pre-processing stage can be divided into.

1. UAVDP: UAV imagery was processed in RealityCapture and Agisoft Metashape, using SfM alignment and dense image matching to reconstruct roofs, façades, and the minaret from the four flight sets. A GCP network of 25 points (15 CPs, 10 ChPs) was imported with the imagery; CloudCompare enforced spatial consistency (alignment to GCPs and stable natural tie points, removal of block drift, harmonization of vertical/horizontal axes) and fixed the block in WGS 84/UTM Zone 38N. After dense reconstruction, CloudCompare was used for QA (outlier filtering, density diagnostics), and meshing/texturing were performed in RealityCapture/Metashape to produce high-quality triangular meshes with photorealistic textures. Automated parameters were image scale = multiscale and 1/2, point density = optimal, minimum matches = 3. The ≈ 3450 images were successfully calibrated; the relative change between initial and optimized intrinsics was $\approx 1.3\%$, and the median matches per calibrated image were ≈ 22000 . The orthophoto overlap map (Figure 14) shows 100% of the area in the “5+” class (optimal stitching). Table 1 summarizes GCP-based georeferencing errors for the UAV block (CPs and ChPs in X/Y/Z).

Table 1. Errors for the georeferencing of GCPs with UAVDP.

Category	Control Points (m)			Check Points (m)		
	X	Y	Z	X	Y	Z
Mean	−0.0019	0.0012	−0.0108	0.0175	0.0031	0.0197
Sigma	0.0295	0.0336	0.0524	0.0450	0.0392	0.0568
RMS error	0.0296	0.0337	0.0534	0.0483	0.0394	0.0592

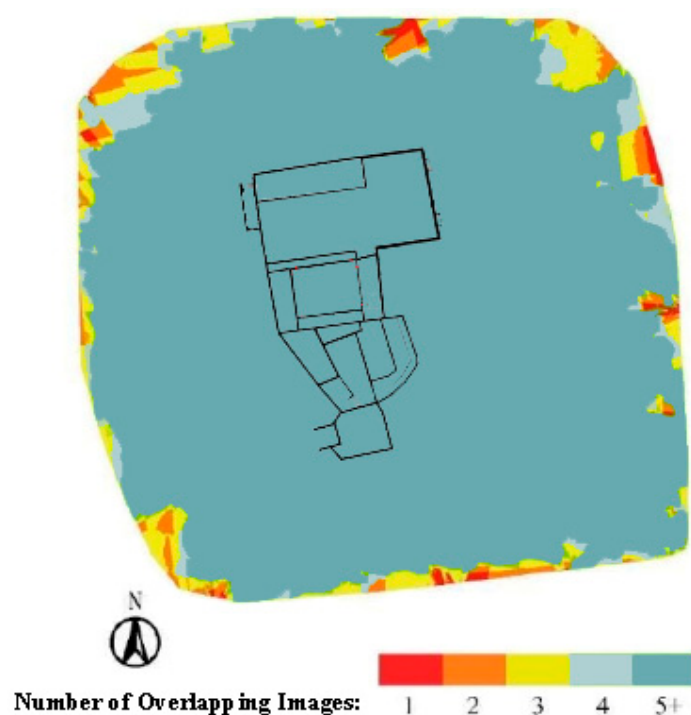


Figure 14. Quality of UAVDP for the mosque.

The deliverables included orthophotos, textured meshes, and a dense PC totaling ~ 295 million points (Figure 15). For HBIM intake, indexed PC packages were exported via Autodesk ReCap (Photo/Pro) as RCP/RCS, alongside the standard mesh and orthophoto products.

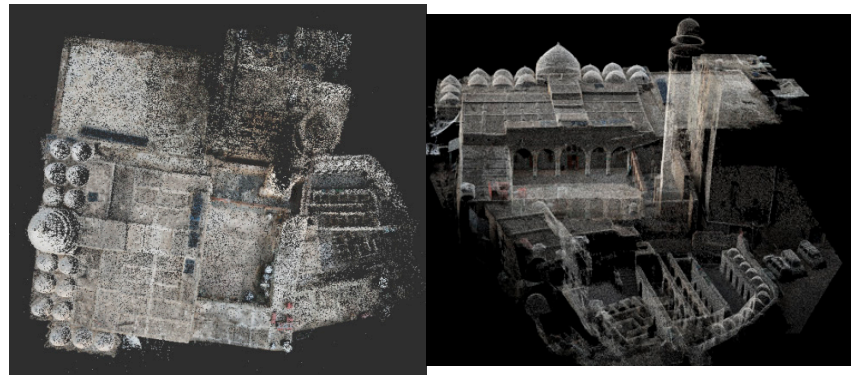


Figure 15. Dense PC of the mosque acquired by UAVDP surveying.

2. TDP: imagery captured with a Canon EOS 5D Mark II was processed in Agisoft Metashape v2.2.1 and Autodesk ReCap (Photo), with CloudCompare v2.13 used for QA, scaling, and spatial harmonization. Approximately 4000 terrestrial photographs were imported into Metashape; alignment was run with accuracy = High, and self-calibration optimized camera intrinsics and exterior orientation from the image network, yielding an initial sparse PC (Figure 16).

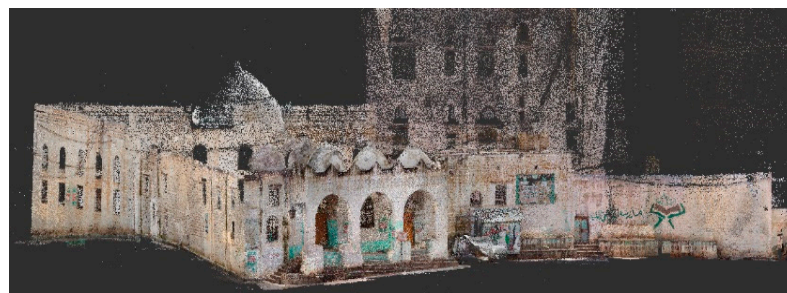


Figure 16. PC of the mosque acquired by TDP surveying.

The GCP network distributed across façades and the courtyard was then introduced and manually marked: 20 valid GCPs (comprising 14 control points, CPs, for georeferencing and 6 check points, ChPs, for independent accuracy checks) were used to optimize the bundle, reduce residuals, and improve absolute pose. Dense reconstruction (MVS) at high quality produced a dense PC of ≈ 65.4 million points, which was subsequently refined via manual filtering and region adjustments to isolate the target façades (Figure 17).



Figure 17. Refined dense PC of the mosque after manual filtering.

A 3D mesh (height-field reconstruction) was generated and textured from the original photographs to obtain a photorealistic surface. Because TDP blocks are initially relative (arbitrary scale and datum), geometric scaling and orientation correction were applied: courtyard baselines measured along the four sides (Figure 12c) served as references to compute an average scale factor in CloudCompare, which, together with the GCP-constrained optimization, registered the TDP model to WGS 84/UTM Zone 38N and ensured seamless integration with the UAV-derived datasets. Finally, indexed deliverables were prepared in Autodesk ReCap (Photo/Pro) (RCP/RCS) for HBIM intake, yielding a metrically reliable, high-detail model suitable for architectural documentation and HBIM integration.

3. SP: A raw set of 50 images underwent radiometric pre-processing in Capture One 7 (color balance, tonal normalization), followed by HDR fusion and panoramic stitching in HDR Expose 3 and SNS-HDR Pro to produce seamless 360° panoramas. Quality control screened focus, exposure consistency, and stitching geometry; automated routines removed tripod shadows, normalized contrast/brightness, and applied lens-geometry calibration to mitigate residual distortions. For spatial integration, GCPs established before capture were measured and subsequently used to georeference the stitched panoramas within the project's coordinate reference system (WGS 84/UTM Zone 38N). Panoramas were then aligned and registered to the UAV/TDP products via stable tie points in CloudCompare v2.13, which also handled artifact clean-up (outlier filtering) and provided diagnostics for registration residuals. Where relevant to downstream modeling, key architectural features (domes, façades, and minaret segments) were segmented from the spherical imagery to guide targeted refinement and interpretation. The optimized panoramas were processed to generate a dense PC of $\approx 7,845,000$ points, enhancing interpretability in areas where conventional photogrammetric lines of sight were limited.

3.2.3. Data Integration

To obtain a single, metrically coherent 3D representation from heterogeneous surveys, PCs from UAVDP, TDP, and SP were fused within a unified geodetic frame (WGS 84/UTM Zone 38N). Pre-processed datasets were integrated in CloudCompare v2.13 via a staged strategy that leverages the complementary strengths of each modality, while conserving absolute geodetic control via the GCP/ChP network. The end-to-end workflow from acquisition through pre-processing, correction, and staged fusion is summarized schematically in Figure 18.

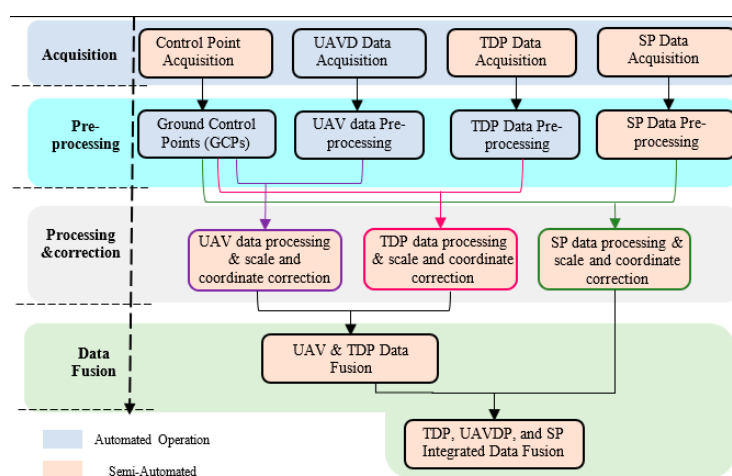


Figure 18. Method chart of data integration from multiple data sources of UAVDP, TDP, and SP.

The first fusion stage integrated the complementary PCs from UAV and TDP. The UAV cloud, already fixed in WGS 84/UTM Zone 38N via GCPs, was adopted as the geometric backbone. The TDP block was first constrained internally (bundle optimization with its GCP set and courtyard tape baselines), then imported to CloudCompare and co-registered to the UAV reference in two steps: (i) manual picking of stable features (edges, corners) to obtain a coarse transform; (ii) refinement by ICP, which first establishes nearest-neighbor pairs by minimizing the Euclidean distance between points, as detailed in Equation (8). Subsequently, these pairs of corresponding points served as the foundation for determining transformation parameters using the least-squares method, as outlined in Equation (9).

$$\hat{i} = \underset{i}{\operatorname{argmin}} \|\vec{p}_i - \vec{q}_j\|^2 \quad (8)$$

$$\hat{R}, \hat{t} = \underset{R, t}{\operatorname{argmin}} \sum_{i=1}^N \|\left(R \vec{p}_i + \vec{t}\right) - \vec{q}_j\|^2 \quad (9)$$

where $\hat{i}$ denotes the index of the nearest neighbor of p_i in the UAV cloud; p_i and q_i are points from the TDP and UAV clouds, respectively; and $\hat{R}, \hat{t}$ are the estimated rigid transformation parameters.

In the second stage (SP ingestion), SP PCs were merged with the previously fused UAV–TDP model to complete visibility-limited sectors (minaret flanks, tight courtyard corners). Before registration, the SP panoramas were tied to the project frame by marking a small set of visually stable landmarks/GCPs, jamb corners, cornice breaks, and parapet edges identifiable in both the panoramas and the UAV–TDP cloud. Because SP reconstruction may carry an arbitrary scale, co-registration in CloudCompare v2.13 followed a two-step procedure: (i) a coarse similarity transform from manually picked correspondences; then (ii) Similarity-ICP (SICP) refinement solving jointly for scale s , rotation R , and translation t . Low-confidence SP regions were masked, and overlap was restricted to well-observed façade belts to avoid bias from uneven sampling.

3.2.4. Two-Dimensional Drawing and Three-Dimensional Modeling

Registered, fused PCs (UAVDP, TDP, SP; WGS 84/UTM Zone 38N) formed the geometric backbone for generating authoritative 2D drawings and reality-based 3D models suitable for downstream GIS/HBIM integration. Processing followed two complementary tracks aligned to metric fidelity and downstream HBIM interoperability. First, in Agisoft Metashape v2.2.1 and RealityCapture, oriented imagery yielded dense reconstructions and texture-ready triangulated meshes. Second, in CloudCompare v2.13, the fused PC was segmented by architectural feature (e.g., minaret, domes, and façades), cleaned, and exported for either surface reconstruction or direct PC visualization. For HBIM intake, consolidated PCs were converted to e57 $\rightarrow$ RCP/RCS in Autodesk ReCap (Photo/Pro) to enable indexed, lightweight linking into Autodesk Revit v.2024.

- Two-dimensional drawings. Oriented imagery (UAV/TDP) was orthorectified to produce façade and roof orthophotos on appropriate projection planes, conserving planimetric accuracy and surface-condition cues required for decay mapping. In parallel, the fused PC was sliced and projected along predefined cut planes (plans, elevations, sections) to obtain clean geometric scaffolds. Drafting and annotation were completed in AutoCAD from exported DXF/OBJ/GeoTIFF assets (with minor tonal adjustments in Photoshop where necessary). The resulting drawings, plans, elevations, sections, and façade/roof orthophotos are issued at declared scales and tolerances and retain CRS metadata to ensure traceability into the ArcGIS 10.8.1 and HBIM environments.

- Three-dimensional modeling. Two routes were adopted according to target use: (i) mesh-from-images (Agisoft Metashape (v. 1.8.3)/RealityCapture (v. 1.5.1)) to generate triangulated, texture-ready meshes with high visual realism; and (ii) mesh-from-points (CloudCompare), where surface-true geometry and dimensional extraction are paramount. The fused cloud was segmented by architectural feature (e.g., minaret, domes, façades), cleaned, and, where necessary, converted to watertight surfaces with minimal smoothing and localized hole bridging to restore continuity without compromising measurement integrity. Texture maps were derived from the original imagery, while full-resolution models were conserved for measurement and HBIM authoring. Consolidated clouds were exported as E57 and indexed in Autodesk ReCap (Photo/Pro) to RCP/RCS for efficient linking into Autodesk Revit. Mesh assets were delivered in OBJ/FBX with textures. All outputs carry persistent identifiers, units, and CRS tags, enabling reliable coordination between the GIS thematic mapping (decay/crack/material layers) and the HBIM model, where architectural elements are parameterized for subsequent semantic attribution and conservation planning.

3.2.5. GIS Platform

Outputs from the hybrid surveys (UAVDP, TDP, and SP) and the accompanying multidisciplinary documentation were normalized to the project CRS (WGS 84/UTM Zone 38N) and prepared for ingestion into a geographic information system. Within the GIS environment, orthorectified façade/roof orthophotos, section lines, and feature-segmented point-cloud derivatives were used as authoritative basemaps for material inventory and decay mapping, following practices reported in the literature [44]. Feature datasets were authored in AutoCAD Map 3D and transferred to ArcMap as typed feature classes (e.g., Materials, Cracks, Detachments, Deformations, Construction_Phases). Topology rules (no gaps/overlaps within polygons, correct line connectivity, snap tolerances) were enforced to guarantee geometric consistency and to enable reliable geoprocessing (overlay, dissolve, spatial join, and area/length statistics). Using these structured layers, the workflow produced thematic maps that (i) depict the spatial distribution of principal materials and finishes; (ii) classify deterioration phenomena crack traces as polylines, detachments/voids as polygons, and deformation zones as areal belts derived from visual inspection and photogrammetric evidence; and (iii) relate damage to construction phases by intersecting pathology layers with phase polygons. Where available, attributes captured element identifier, material type, condition, severity class, data source (orthophoto/field note/PC slice), and survey date, enabling reproducible queries and filters. The resulting 2D/3D GIS scenes support diagnostic analysis, priority ranking, and cartographic communication; they also export as GeoPackage/shape/GeoJSON for linkage with HBIM (shared coordinates and element IDs), ensuring interoperability between GIS thematic mapping and the HBIM environment used for conservation planning [54].

3.2.6. HBIM Creation

An HBIM of the Great Mosque was authored in Autodesk Revit 2024, using the registered, fused RCP/RCS PCs (UAVDP, TDP, SP; WGS 84/UTM Zone 38N) as the primary geometric reference and the authoritative 2D drawings (plans, elevations, sections, and façade/roof orthophotos) as drafting scaffolds. Shared coordinates were established to conserve geodetic consistency with the survey/GIS datasets. Modeling proceeded from a level grid framework and feature-by-feature reconstruction of major elements, load-bearing walls, arcades, domes, vaults, and the minaret with families selected or custom-built to match measured profiles and junctions. Where required, families were parameterized to capture nonstandard heritage geometries (e.g., variable dome springing, tapered piers,

crenellations) while maintaining a restrained level of development appropriate to conservation analysis and interoperability. A lightweight parameter schema was implemented to support semantic enrichment and downstream linkage with GIS and thematic diagnostics. Core instance/type parameters include: *Element_ID* (persistent identifier), *Material_Type*, *Construction_Phase*, *Condition_State*, *Decay_Class* (e.g., crack, detachment, discoloration), *Data_Source* (orthophoto/PC slice/field note), and *Survey_Date*. Values follow controlled vocabularies aligned with the GIS feature classes (Materials, Cracks, Detachments, Deformations, Construction_Phases), enabling round-trip queries by key and spatial overlay via shared coordinates. Material assignments were defined from the survey-driven inventory (e.g., local stone/limestone, timber, gypsum/al-Qdad) to ensure consistency between visual appearance and analytical labeling. To facilitate analysis and communication, the model incorporates view templates (plan/elevation/section/axonometric) and element filters that render condition and phase attributes directly in Revit views. Deliverables were prepared in RVT/IFC (model exchange), DWG/PDF (2D sheets), and RCP/RCS (reference clouds), conserving units and CRS tags. This HBIM serves as the authoritative, geodetically referenced container that consolidates geometry and attributes for conservation planning, quantity estimation, and integration with GIS thematic mapping and subsequent data enrichment.

4. Results

4.1. Integrated Point Clouds (PCs)

The staged fusion produced a high-density, metrically referenced composite in WGS 84/UTM Zone 38N that closes visibility gaps along the minaret flanks and in tight courtyard corners (Figure 19). Quantitatively, UAVDP–TDP co-registration via ICP achieved RMS residuals <0.013 m across the overlap belts, while ingestion of SP point sets via SICP converged with residuals <0.012 m, consistent with the local CP/ChP envelope. A color-coded deviation spectrum was used to visualize patch-wise differences across the fused model, enabling rapid detection of any local misfits. Input data volumes reflect the complementary roles of each modality: the UAVDP survey yielded ~295 million points (global coverage and roofscape), and the TDP campaign contributed ≈ 65.4 million points (façade-scale detail); SP provided additional occlusion closure in constrained sectors. Following fusion, the composite therefore comprises >360 million points, conserving UAVDP planimetric continuity while injecting TDP vertical/material detail and SP gap-filling coverage. For downstream use, the fused dataset was exported (XYZ/e57) and indexed in Autodesk ReCap (Photo/Pro) to RCP/RCS for lightweight linking into Autodesk Revit as the authoritative reference cloud for HBIM authoring. Table 2 summarizes the registration workflow and alignment metrics (ICP for UAV–TDP; SICP for SP ingestion) associated with the integrated model shown in Figure 19.

Table 2. Data fusion process and alignment results.

Step	Description	Software/Method Used	Key Metrics/Results
UAVDP + TDP fusion	Co-register the TDP PC to the GCP-anchored UAV reference (project CRS: WGS 84/UTM Zone 38N) using manually picked correspondences for a coarse transform; then, refine with rigid ICP.	CloudCompare v2.13, ICP (rigid, R,t)	ICP RMS < 0.010 m (overlap zones); alignment verified by spot M3C2 checks; fused cloud conserves UAV planimetry and injects TDP façade detail.
SP + UAVDP–TDP fusion	Integrate SP point sets (360° panoramas) with the fused UAV–TDP model: coarse similarity transform from matched landmarks, then SICP refinement solving scale <i>s</i> , rotation <i>R</i> , translation <i>t</i> ; low-confidence SP regions masked/down-weighted.	CloudCompare v2.13, SICP (similarity, <i>s</i> , <i>R</i> , <i>t</i>)	Residuals within local CP/ChP envelope where overlap exists; SP retained primarily for completeness/visualization (not primary metric control).

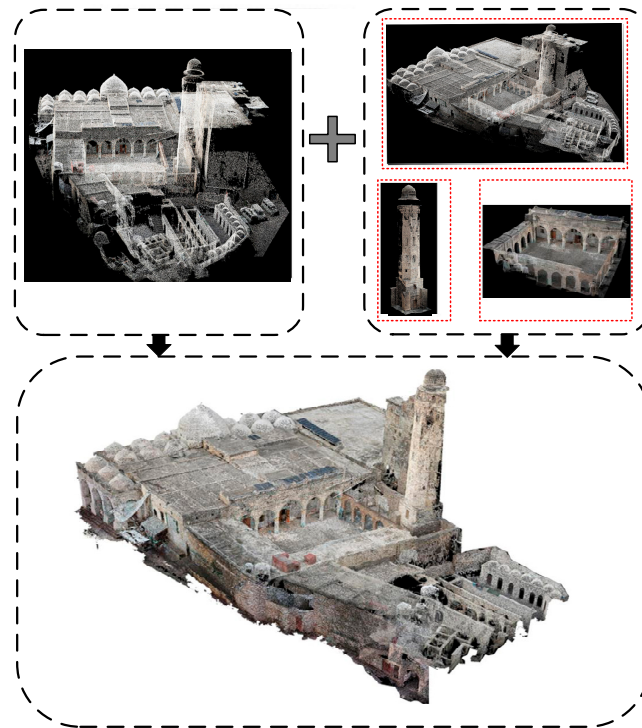


Figure 19. Integrated PC model from UAVDP, TDP, and SP for the mosque.

4.2. Two-Dimensional Drawings and Three-Dimensional Models

The fused survey datasets yielded a complete suite of 2D and 3D deliverables that serve as authoritative baselines for analysis and HBIM authoring. Orthorectified façade and roof orthophotos conserve planimetric fidelity and surface condition, enabling direct reading of cracks, efflorescence, and weathering; a representative roof-plan projection with the corresponding rendered top view is shown in Figure 20.

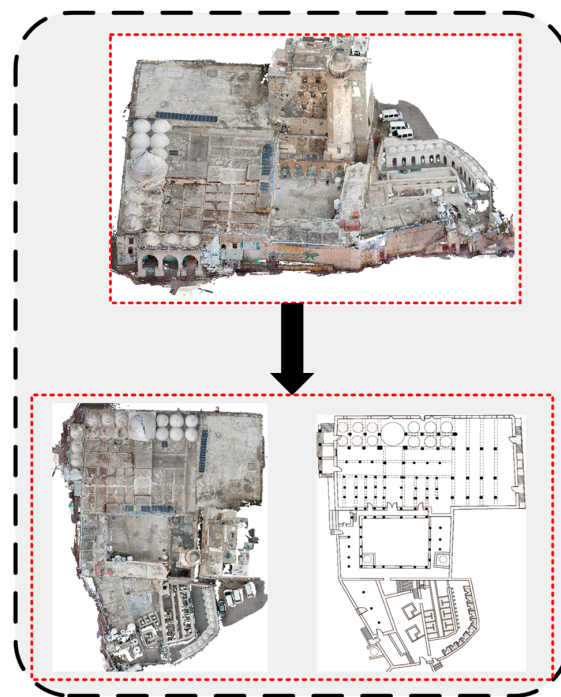


Figure 20. The roof plan projection and rendered top view of the mosque.

From the registered PC, plans, elevations, and sections were generated by controlled slicing and projection, producing clean geometric scaffolds at declared scales. Figures 21 and 22 illustrate cross-sections through the courtyard and minaret (a–a and b–b), clarifying span systems, level changes, and the relationship between the prayer hall, courtyard, and perimeter elements. As summarized in Table 3, orthophotos were used as the primary substrate for decay mapping and material reading, while line drawings provided authoritative geometric constraints for HBIM sectioning and dimensioning; the table contrasts both across metric representation, visual information, automation/efficiency, and production constraints.

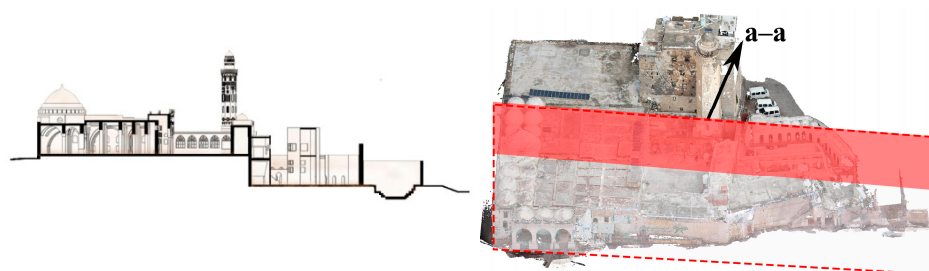


Figure 21. Cross-section of a–a for the courtyard and minaret of the mosque.

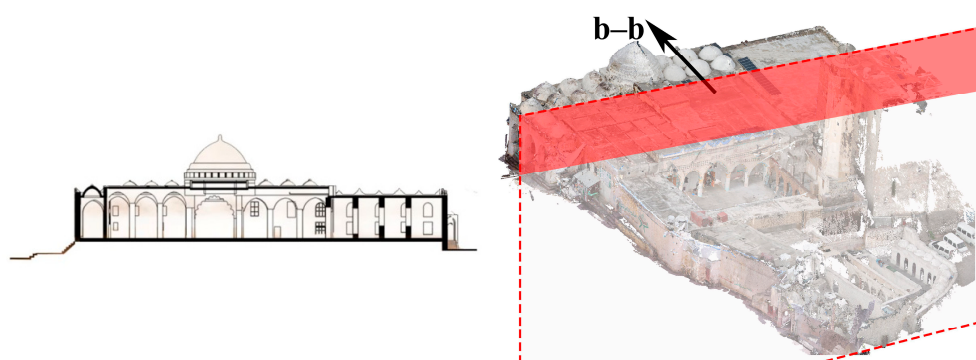


Figure 22. Cross-section of b–b for the courtyard and minaret of the mosque.

Reality-based 3D models capture the mosque's morphology with high geometric and visual fidelity. The overall model integrates exterior façades, roofscape, and courtyard into a coherent envelope suitable for precise dimensional extraction and HBIM reference (Figure 23). Feature-level models resolve architectural components, minarets, domes, crenellations, and façade details supporting element-wise diagnostics and parameterization within HBIM (Figure 24).



Figure 23. Three-dimensional Reality-based model of the mosque.



Figure 24. Three-dimensional Reality-based model of architectural elements.

Table 3. Comparison between line drawings and orthophotos used in this study.

Criterion	Line Drawings	Orthophotos
Metric representation	Scale is declared, and geometry is derived from registered PCs, but final depiction involves operator interpretation; complex curvatures and fine profiles may be generalized.	True-to-scale, orthographically corrected imagery conserving planimetric fidelity; complex forms are represented directly from photogrammetric control with minimal generalization.
Visual information	Emphasizes edges, outlines, and schematic structure; material cues and surface condition must be annotated symbolically and may be omitted.	Captures textures, color, patina, and surface condition (e.g., cracks, efflorescence, and weathering), enabling direct visual diagnostics and material reading.
Automation and efficiency	Higher manual input (slicing, feature extraction, drafting); quality depends on operator skill; reproducibility varies; suitable for selective abstraction.	Highly automated pipeline (SfM, dense PC, orthorectification); consistent, repeatable outputs; reduced human error; efficient for large areas once inputs are prepared.
Production constraints	Time-consuming for intricate heritage fabric; drafting workload scales with complexity; lighter files and simple toolchains ease distribution.	Dependent on image quality, coverage, and control, larger data volumes and storage; processing time scales with site complexity but less with manual labor.

An overview of the modeling methods adopted and their suitability for exterior, interior, and feature-scale reconstruction is summarized in Table 4. Collectively, these outputs provide metrically reliable, interoperable assets that link condition-aware 2D analy-

sis with 3D HBIM representation, directly supporting conservation planning and material quantification.

Table 4. Three-dimensional modeling methods for the mosque.

Modeling Method	Required Data	Survey Equipment	Representative Software	Modeling Accuracy	Modeling Cost and Efficiency	Suitable for the Mosque
Traditional 3D Software Modeling	Minimal survey constraints	No specific	3ds Max, SketchUp, Rhino, Maya, etc.	Low (shape-oriented)	Low automation, time-consuming	General massing/rough models
Image-Based Modeling	Images	UAVDP, TDP, SP	Agisoft Metashape, RealityCapture	Moderate accuracy, high realism	High automation, shorter time, lower cost	Exterior and interior detailed views
PC-based Modeling	PC data	UAVDP, TDP, SP	CloudCompare, RealityCapture, AutoCAD, Recap, etc.	High (surface-true)	High data volume; longer processing	Detailed reconstruction of features

4.3. HBIM Implementation

BIM is widely recognized for standardized data structures, reduced information loss, and high production accuracy [57]. Yet, despite its robust capacity to ingest and manage PCs, conventional BIM remains insufficient for heritage conservation because typical libraries lack parametric objects and material vocabularies specific to historic fabric [16,58]. HBs are characterized by complex, heterogeneous, and irregular geometries [8,59]; accordingly, the precise formal characterization of architectural components is a prerequisite for HBIM, often requiring the definition of new, custom parametric objects [16,60].

In this study, building components were first classified by geometric complexity, frequency, and detail into regular versus irregular surfaces. Regular elements (floors, roofs, columns, walls) present comparatively straightforward geometry, whereas traditional architectural features of the mosque, doors, windows, arches, domes, and the minaret were treated as irregular due to their intricate profiles and junctions. Based on this taxonomy, the HBIM implementation followed a two-pronged strategy: (1) development of a parametric architectural-object library capturing the mosque's distinctive features; and (2) assembly of the overall building model that integrates regular and irregular components into a coherent, metrically faithful digital representation suitable for subsequent analysis and conservation planning.

4.3.1. Modeling of the Architectural Object Library

An extensive parametric family library was authored to address the well-documented shortage of heritage-ready BIM content and to support efficient, metrically faithful HBIM authoring [16]. Given the mosque's irregular geometry and fine architectural detail, different families were developed to represent various building elements such as domes, windows, doors, arches, the minaret, and ornaments, with LOD 300 for architectural components and LOD 350 for structurally/diagnostically critical elements. For clarity and downstream use, the library was organized into two groups: (a) architectural elements (windows, doors, ornaments) and (b) structural elements (arches, domes, and minarets). To balance fidelity and performance, selective simplification of 10–30% was applied depending on local complexity. Families were created in Autodesk Revit 2024, using the fused RCP/RCS reference cloud (UAVDP/TDP/SP) together with façade/roof orthophotos as metric baselines. A 2D vector workflow (AutoCAD) was evaluated but ultimately discarded in favor of intrinsic parametric 3D authoring in Revit. For complex free-form profiles, a Rhino bridge (Evolute Tools PRO) was used to derive governing curves/surfaces, and then imported for parameterization to conserve measured curvature and junction logic. Figure 25 summarizes the end-to-end workflow from survey references to HBIM family

deployment, with element types, defining details, and modeling choices documented in Table 5 to ensure transparent reuse and extension.

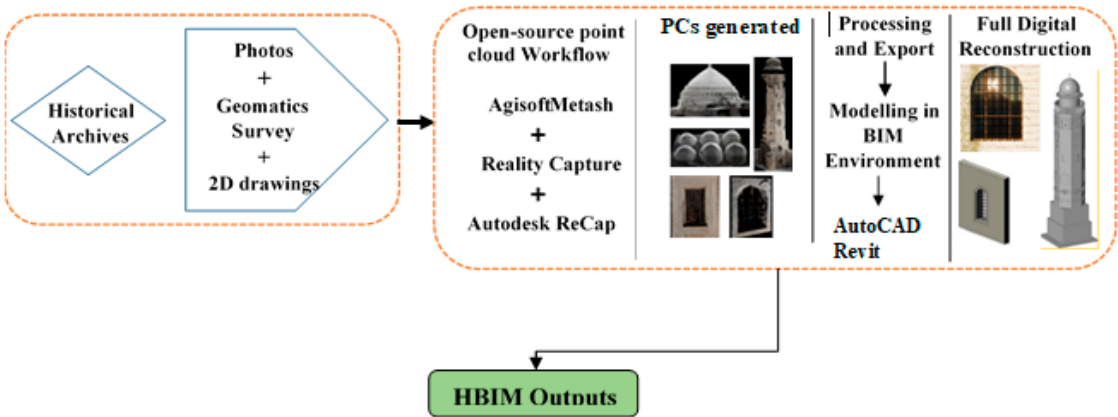
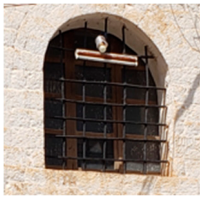
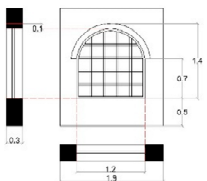
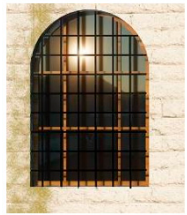
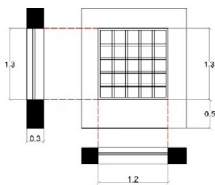
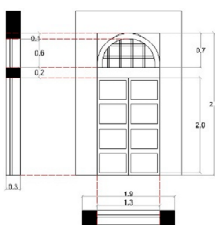
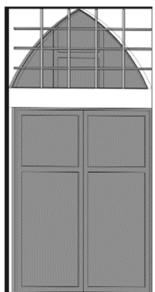
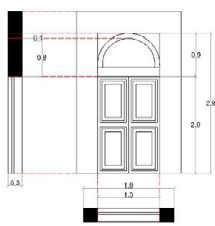
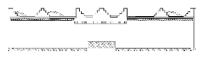


Figure 25. Workflow for implementing and modeling an architectural object library.

Table 5. Library of architectural objects (HBIM families) and components printed using 3D printer.

Families	Types	Data Collection		Point Clouds (PCs)	Three-Dimensional Modeling of Families
		Photos	Photos 2D Drawing		
Structural Elements	Minaaret				
	Domes				
	Arches				

Table 5. Cont.

Families	Types	Data Collection		Point Clouds (PCs)	Three-Dimensional Modeling of Families
		Photos	Photos 2D Drawing		
Architectural Elements	Windows				
	square				
	door with a window				
	Doors				
	ornaments				

1. Windows: There are two façade window types: (1) semicircular and (2) square. Both are timber-framed units set flush to the interior face of the wall, leaving the exterior wall thickness expressed as a reveal. Each includes wooden muntins that subdivide the opening, nine small lights in the semicircular type, and six in the square type, and the lights are glazed with glass panels. For security, an iron mesh grille is mounted externally. HBIM followed an equivalent workflow for both types, with variations only in geometry, size, sill/head height, and profile: (a) define a new window family in Revit; (b) create the host-wall opening from field measurements, using extrusions derived from straight and curved profiles; (c) for the semicircular type, model the arch ring/intrados; (d) model the window frame (jambs, head, sill); (e) generate the two operable leaves and the internal muntin grid that carries the glass panels; (f) assemble all subcomponents into the final 3D family. Materials were then assigned glass to the panes and wood to the frame and leaves, to ensure consistent visualization and quantity take-off.

2. Doors: They are wooden doors, where one door consists of two wooden panels, one of which opens when used. The doors have almost the same specifications, with some minor differences, which led to their division into two types: 1. A wooden door topped by a semi-circular upper window is used for lighting; 2. a wooden door containing decorated panels and topped with a solid semi-circular stone arch covered with plaster. A similar modeling process was performed to generate distinct families of doors. The specific details of each type vary in terms of the particular geometry of the door, the division and decoration of the wood panels, and the framing elements around the door to obtain 3D modeling. In addition to modeling the openings above each door.
3. Ornaments: The roofline ornaments consist of triangular finials carved on both faces that mark the ridge line. They exhibit irregular geometries and variable complexity, reflecting traditional craftsmanship. Each element is constructed in stone and coated with a gypsum layer, which contributes additional surface articulation. Given these irregularities and the fine-grained relief, accurate HBIM representation required substantial effort: $\approx 15\text{--}20$ h per piece were devoted to capturing asymmetries, edge profiles, and bidirectional carvings. The modeling process emphasized faithful reproduction of unique features (planform variation, relief depth, and surface transitions), ensuring that the resulting digital surrogates conserve the geometric and material character of the originals and are suitable for reliable documentation and subsequent analytical tasks.
4. Arches: The mosque incorporates two principal arch typologies. (1) External arches closely follow the horseshoe pattern, with an intrados that extends beyond a semicircle ($>180^\circ$). (2) Interior (courtyard) arches comprise two primary styles: horseshoe unit arches and pointed arches characterized by a sharply defined, angular apex. Beyond their role in transferring vertical loads and stabilizing the superstructure, these arches articulate the spatial rhythm of the prayer hall and courtyard and contribute significantly to the ensemble's esthetic and ceremonial expression. For HBIM classification, the Uniclass 2015 system was adopted for its breadth and interoperability; a project-specific sub-classification tailored to Islamic architectural morphologies was then introduced and embedded as shared parameters (e.g., Arch_Type, Profile_Angle, Span, and Thickness). This schema enables consistent querying, tagging, and scheduling, and is documented in the parametric objects table, providing a clear semantic mapping for each arch type alongside the other architectural features.
5. Domes: Domes are architectural structures characterized by semicircular/spherical geometry. In the mosque, small domes rest on circular drums, whereas the principal dome springs from a polygonal base; construction employs stone and concrete, and surfaces carry distinctive decorative programs. Structurally, the dome form distributes loads efficiently, improving resistance to wind and other lateral actions. Capturing these geometries with metrical fidelity required extensive geometric analysis to reproduce curvature, base transitions, and ornament deployment in the 3D model. Specifically, the parametric workflow included the following:
 - Surface curvature analysis. The dome envelope was modeled and validated using NURBS (Non-Uniform Rational B-Splines) to ensure an accurate representation of meridional and hoop curvatures in the digital model.
 - Base geometry study. The transition from polygonal base to spherical cap (large dome) and cylindrical drum to cap (small domes) was examined to reflect structural load paths and to conserve the measured springing levels and profiles.
 - Material and structure integration. The spatial distribution of stone and concrete sectors was mapped to the geometric substrate to respect construction

logic and to maintain both esthetic continuity and structural integrity in the parametric definition.

- Decorative and color pattern analysis. Geometric motifs and chromatic schemes were surveyed and UV-mapped to the dome surface so that ornamentation is faithfully reproduced and aligned with underlying curvature.

All analyses were embedded in the HBIM environment as parametric controls and metadata, yielding an interoperable, metrically faithful representation of the domes that captures both structural behavior and decorative articulation.

6. Minaret: The minaret comprises four principal sections: (i) a rectangular base (basement/plinth); (ii) a polygonal superstructure (tower/shaft) embellished with decorative plaster inscriptions; (iii) the gallery balcony (muezzin platform); and (iv) a pyramidal pinnacle surmounted by an additional balcony and capped with a white dome (upper termination). The overall height is approximately 25 m. Owing to the minaret's height and geometric complexity, field documentation was stratified into three survey packets to ensure full coverage and redundancy: (a) Lower section captured with TDP and SP, resolving near-field detail at the base and lower shaft; (b) Upper section acquired by UAVDP to obtain multi-angle views of the balcony, pinnacle, and dome; (c) Middle section documented with TDP from camera stations on the mosque roof, bridging lower and upper datasets and closing line-of-sight gaps.

During the modeling process for HBIM authoring, the minaret was divided into three sections (bottom, middle, and top) to manage topology, accurate reconstruction, and control tolerances. The following steps were executed:

- Three-dimensional measurement: Sparse and dense PCs were generated from the combined UAVDP, TDP, and SP image blocks. The merged dataset was filtered, cleaned, and segmented in CloudCompare, producing metrically consistent sub-clouds for each architectural section.
- Surface reconstruction: RealityCapture and Agisoft Metashape v2.2.1 were used to create textured meshes from the oriented image blocks, ensuring faithful representation of curved and irregular profiles.
- Texturing and visualization: High-resolution texture maps were derived from source imagery to conserve surface materials, plaster details, and ornamental inscriptions. Each minaret section was geo-referenced within the project's coordinate reference system (WGS 84/UTM Zone 38N) and exported as RCP/RCS via Autodesk ReCap for efficient linking into Autodesk Revit 2024. For geometrically complex features, a Rhino–Revit bridge (Evolute Tools PRO) was employed to generate governing curves and surfaces, then parameterized in Revit to maintain accurate curvature and junction logic. This approach enabled precise automated placement of each section within the HBIM environment, ensuring alignment integrity and continuity between adjoining parts. Finally, the architectural object library was then completed and uploaded to the Revit project to build the HBIM mosque model. The minaret's LOD was set to LOD 350, providing high geometric resolution, especially in damaged or deformed areas, to support diagnostic mapping, material assessment, and conservation planning.

4.3.2. Implementation of a 3D HBIM Model

Following multi-source acquisition, fusion, and cleaning of the registered PCs (UAVDP/TDP/SP) and the authoring of the parametric family library, a metrically faithful HBIM of the Great Mosque was implemented in Autodesk Revit 2024. The RCP/RCS reference cloud (indexed via Autodesk ReCap) and façade/roof orthophotos served as authoritative baselines. Project shared coordinates were set to WGS 84/UTM Zone 38N

to maintain consistency with the survey frame and to ensure downstream interoperability with GIS layers. Modeling proceeded in a controlled sequence to conserve accuracy and performance. First, levels, grids, and control views were established from the point-cloud elevations and orthophoto axes. Exterior and courtyard wall systems were then traced directly against the cloud, using locked dimensions and reference planes to stabilize alignments and thicknesses. Openings (doors, windows) were placed using the previously authored LOD 300 families, constrained to host geometry and verified against the cloud by spot checks (offsets and edge snaps). Structural and diagnostically critical elements, arches, domes, and the minaret were inserted using LOD 350 families. Where free-form continuity was required (e.g., complex intrados/extrados or cornice transitions), governing curves/surfaces were derived in Rhino (Evolute Tools PRO) and imported as SAT references, then parameterized in Revit to maintain measured curvature and junction logic. To manage complexity, worksets and view templates were used to partition the model by system (envelope, structure, features) and by zone (exterior façades, courtyard, and roof). Section boxes and high-detail views enabled local verification of offsets and radii against the cloud, while type/instance parameters captured dimensional controls (span, rise, thickness) for reproducible edits. The resulting HBIM model conserves the mosque's irregular morphology while remaining lightweight enough for authoring and coordination. It also establishes the geometric scaffold required for subsequent data enrichment and linkage to GIS thematic layers. Figure 26 illustrates the modeling stages and the final construction of the HBIM model of the Great Mosque.

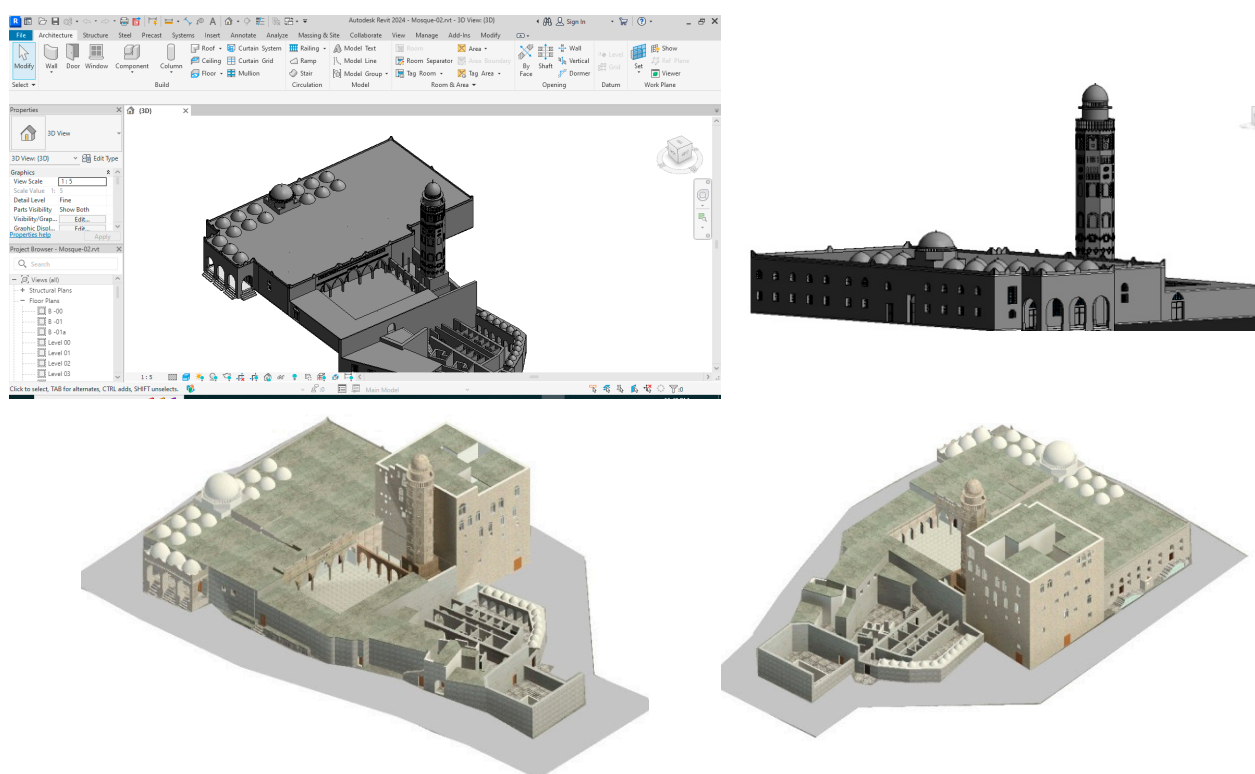


Figure 26. Final HBIM overview of the mosque of Ibb.

4.3.3. Data Enrichment

The data enrichment phase of the HBIM environment sought to augment the existing 3D model by incorporating multidisciplinary material, such as architectural specifications, historical records, pictures, and various 3D surveying datasets. The precision of the data gathering method, the comprehensiveness of existing historical records, and the extent of architectural expertise about the HBs were critical determinants in defining the enrichment

strategy. In Autodesk Revit 2024, semantic segmentation was utilized on the HBIM model to facilitate the systematic categorization of architectural elements based on their shape, function, and typology. This segmentation facilitated the distinction of the mosque's components across several Levels of Detail (LoD) and associated Semantic Classification (SC). A first semantic segmentation has been executed, but additional refining is in progress to attain a completely classified HBIM that precisely reflects the architectural and historical attributes of the mosque. Due to Revit's lack of a native LoD framework, the SC was associated with different representation scales according to this criterion: high scale (1:1–1:20) for intricately detailed architectural elements, medium scale (1:50) for principal structural and architectural components, and low scale (1:200) for general or complex architectural assemblies. As a result, the outcome is a model with distinct, intricate components that are easily manageable.

Consequently, five semantic domains were established to hierarchically organize the architectural information. LoD1/SC1: the comprehensive building structure; LoD2/SC2: functional areas; LoD3/SC3: predominant Islamic architectural features that delineate the functional areas; LoD4/SC4: architectural sub-elements that specify the volumetric architectural entity; and LoD5/SC5: particularized detailed architectural components such as ornaments. This hierarchical structure facilitates both detailed and broad visualization of the mosque's components across many dimensions, as demonstrated in Figure 27.

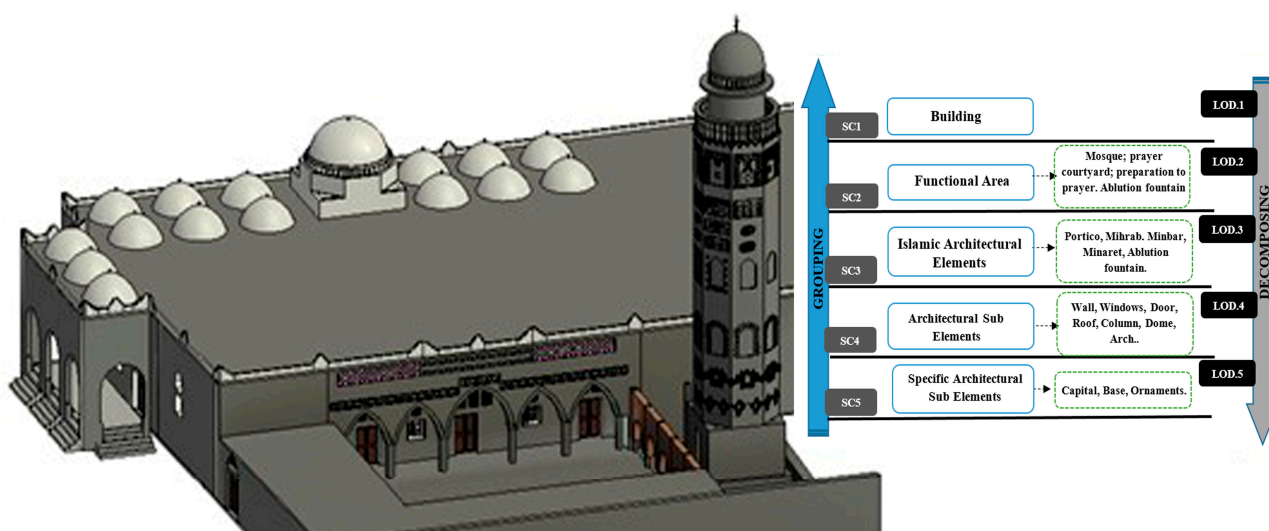


Figure 27. Semantic segmentation of architectural elements based on LoD and SC.

A bespoke relational database was developed within Revit to facilitate the management of non-geometric information associated with each HBIM element, hence supporting the semantic framework. This database retains essential aspects, including historical references, material properties, construction phases, deterioration states, and intervention documentation. The system functions on an entity-relationship basis, facilitating the categorization of digital information and defining relationships within and across elements. Every component received a distinct five-digit identification code, indicating its hierarchical status within the model, ranging from the overarching structure (LoD1) to its specific sub-element (LoD5), hence enabling direct query-based identification. The identifiers are stored in the relational database and can be retrieved using the model's schedules and property tables, as illustrated in Figure 28.

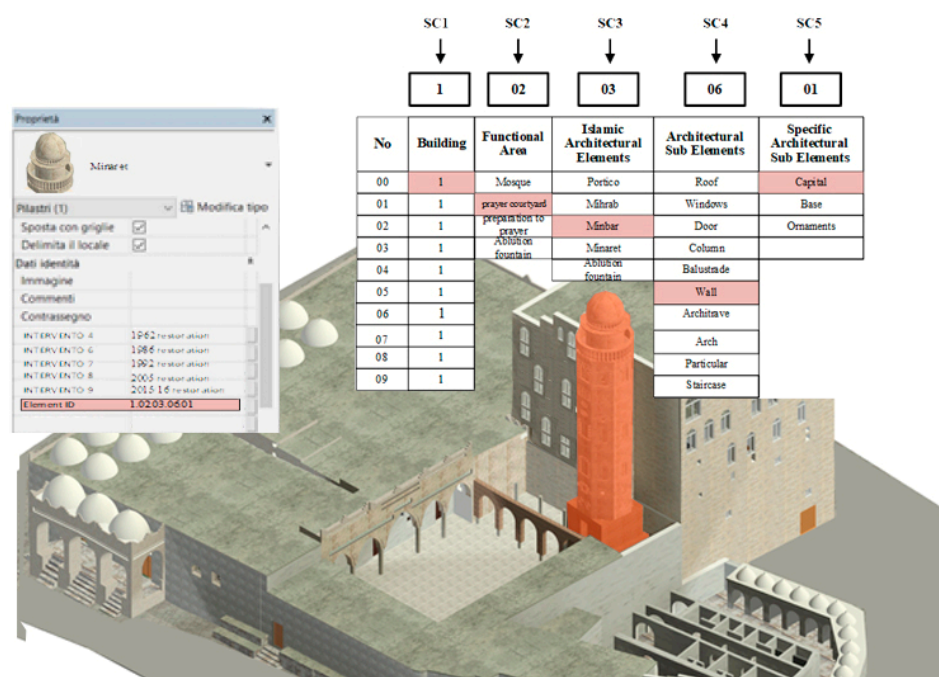


Figure 28. Example of ID code representing the base of the Minaret.

From a conservation standpoint, managing a heterogeneous dataset that includes historical, material, and geometric aspects required the implementation of a customizable material library. This library facilitates the linkage of non-geometric features (textual data, photos, texture maps, deterioration comments, and intervention metadata) to each model element, ensuring that all information is readily accessible for conservation and study. Figure 29 illustrates that the library facilitates the incorporation of material types and textures, enhancing the visual and informational accuracy of the HBIM model. The completed enriched model functions as a thorough digital archive that facilitates historical recording, structural assessment, and conservation strategy development. It also offers complete interoperability with GIS datasets via shared coordinates and unique IDs, facilitating integrated spatial analysis and thematic mapping.

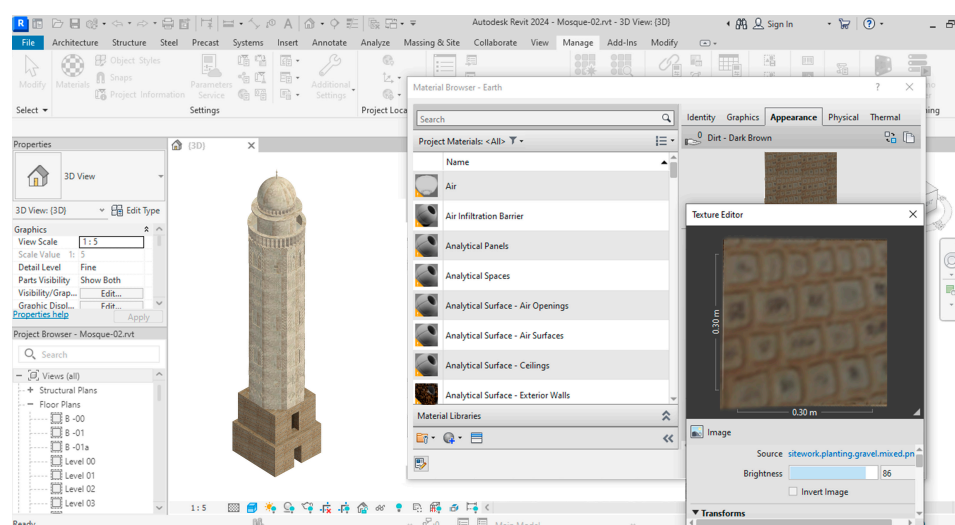


Figure 29. Customizable library for collecting material types.

4.4. GIS Thematic Mapping

Thematic mapping using GIS was essential for the documentation and preservation of the Great Mosque, facilitating the organization of multidisciplinary evidence into queryable geographical qualities that connect qualitative observations with quantitative data. This encompassed the integration of inputs at multiple scales, from the mosque's general structure to façade-level specifics, historical construction phases, and patterns of material degradation. Orthorectified façade and roof orthophotos, aligned to WGS 84/UTM Zone 38N, functioned as definitive base layers in a CAD/GIS workflow (AutoCAD (v.2025) Map 3D → ArcMap). Features were digitized and categorized into typed classes: Materials, Cracks, Detachments, Deformations, and Construction Phases, then validated using topological principles to ensure geometric consistency. Employing this organized schema, relational/Boolean queries and conventional geoprocessing techniques (overlay, dissolve, spatial joins) produced thematic maps that collectively illustrate material distributions, decay extent/severity, and façade-scale structural vulnerabilities over time and building phases. Material-themed layers accentuated spatial variety in brickwork and finishing systems, elucidating relationships and their probable performance under moisture and stress. Because deterioration was markedly higher on the west and north elevations, the analysis concentrated on these two façades (Figures 30 and 31), providing the clearest evidence of vulnerability and decay dynamics.

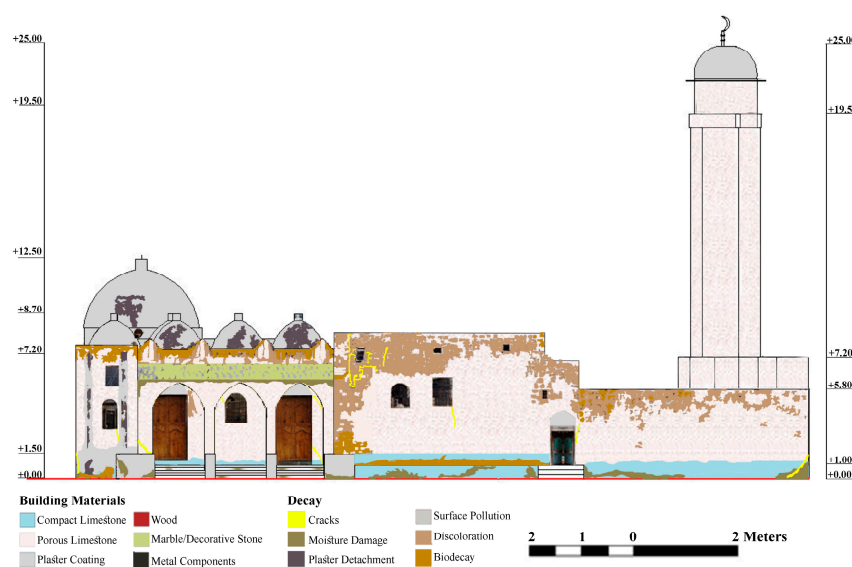


Figure 30. Thematic map of building materials and decay of the west façade.

The thematic maps emphasized notable material variety and structural vulnerability, especially on the western façade (Figure 30). The analysis revealed significant utilization of porous limestone as the principal structural material, supplemented by compact limestone in the lower courses, which are particularly vulnerable to rising damp and environmental degradation. Crack concentrations are present around openings (windows/arches), whereas the separation of plaster coats in multiple regions indicates significant moisture damage. Surface contamination and deterioration were noted in the higher areas of the façade, indicative of extended exposure to environmental elements. Smaller domes display minimal external erosion, but the major entrance, adorned with artistic elements, exhibits signs of aging and surface deterioration. The northern façade (Figure 31) is predominantly composed of porous limestone, while compact limestone at the base is significantly affected by moisture accumulation and capillary rise. Cracking is evident throughout wall surfaces, especially at window joints; lower sections show signs of rising damp, and ex-

tensive parts reveal discoloration from environmental exposure. The biological colonization adjacent to the plinth indicates sustained moisture levels. Additionally, larger domes exhibit upper-sector erosion, but the central minaret remains relatively intact, with just moderate surface deterioration. Moisture-related pathology predominantly affects both façades, with greater severity on the west side, while overlaying cracking at openings and architectural transitions identifies clear priorities for immediate conservation and structural evaluation.

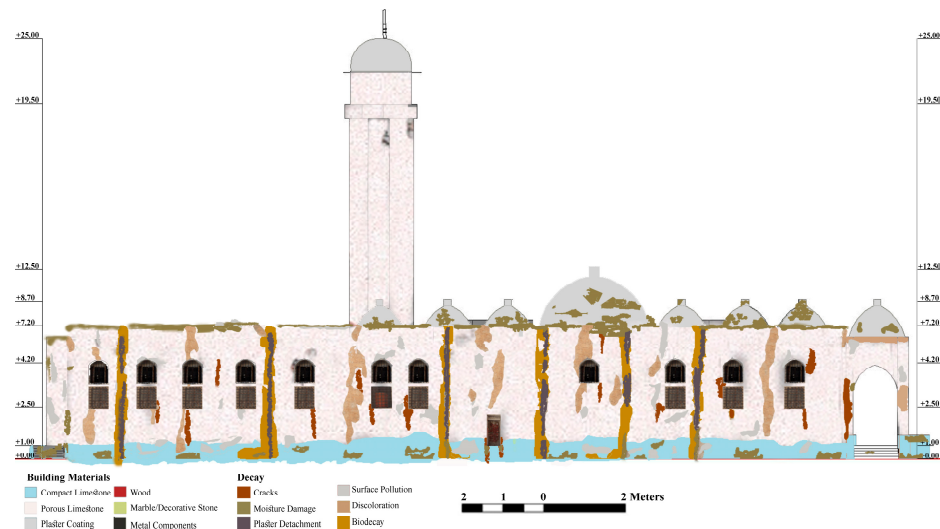


Figure 31. Thematic map of building materials and decay of the north facade.

4.5. Integrating HBIM with GIS

The integration of HBIM with GIS thematic mapping represents a significant advancement in the documentation and conservation workflow for the Great Mosque. Orthorectified façade and roof orthophotos, aligned to WGS 84/UTM Zone 38N, together with feature-segmented derivatives from the fused point clouds (PCs), were organized into GIS layers representing materials, cracks, detachments, deformations, and construction phases. These layers were validated through topology rules to ensure geometric consistency and were subsequently linked to HBIM elements in Autodesk Revit 2024 via persistent element identifiers and shared coordinates, enabling interoperable querying of qualitative observations and quantitative metrics.

Within the HBIM environment, semantic enrichment focused on key architectural components—including walls, roofs, windows, doors, arches, domes, and the minaret—by assigning attributes derived from GIS analysis (material type, phase, condition, severity, provenance, and survey date). This element-level semantic embedding supports dynamic monitoring, allowing condition attributes to be updated during successive inspection campaigns without model reconfiguration. Crack typologies, moisture zones, and plaster detachments were incorporated as parameterized data and visual overrides, while selected crack traces were instantiated as non-structural detail or void elements aligned to the reference point cloud, enabling length and area quantification at the façade or bay scale.

Phase-specific material information (e.g., porous versus compact limestone and surface finishes) was associated with host elements to interpret material behavior at construction interfaces and support compatible intervention design. From a technical perspective, GIS–HBIM integration was achieved by linking GIS thematic layers to HBIM elements through shared coordinates and persistent element identifiers rather than file-based interoperability (e.g., IFC). GIS thematic layers derived from orthophotos and segmented point clouds were first processed and validated within the GIS environment. These GIS layers were then analyzed to extract pathology indicators, such as cracks and moisture

zones, which were subsequently transferred into HBIM as parametric attributes, embedded directly within Autodesk Revit. This approach ensured that spatial consistency was maintained across the dataset, while also supporting dynamic updates as new inspection data was added.

Operationally, the integrated HBIM–GIS framework enabled three key conservation functions: (i) detection-to-action workflows, allowing the identification and visualization of high-severity pathologies—particularly on the western and northern façades—and the generation of targeted intervention views; (ii) materially consistent specification, correlating moisture indicators and porous stone zones with appropriate repair strategies; and (iii) quantitative assessment, including the calculation of crack lengths and detachment areas by zone for restoration planning. By maintaining provenance and survey-date metadata at the element level, the model facilitates temporal comparison of deterioration across monitoring cycles. Overall, GIS provides spatial analysis and thematic classification, while HBIM delivers element-level semantics, visualization, and quantification. This combination translates observed deterioration patterns—such as moisture-induced decay from the plinth to the mid-wall and associated cracking at openings and architectural transitions—into traceable, phase-aware, and quantity-supported conservation strategies.

5. Discussion

This study demonstrates the practical and methodological significance of an HBIM–GIS workflow for recording, diagnosing, and planning the conservation of a complex cultural heritage asset, namely the Great Mosque of Ibb, Yemen, under stringent access and resource limitations. By integrating TDP, UAVDP, and SP, the project achieved a multiscale and multimodal data acquisition strategy that reconciles façade-scale detail with comprehensive building coverage and effective occlusion resolution. Each surveying technique contributed distinct and complementary information. Terrestrial digital photogrammetry (TDP) provided high-resolution façade textures and detailed geometric data, capturing intricate carvings and material condition indicators that form a reliable basis for accurate documentation of architectural elements [12,16]. UAV-based digital photogrammetry (UAVDP) supplied roofscape data and access to otherwise unreachable components, which proved essential for understanding the mosque’s spatial context and identifying areas susceptible to structural weakness [61,62]. Spherical photogrammetry (SP) addressed visibility-restricted zones, captured complex intrados and extrados, and delivered detailed representations of ornate architectural features such as domes and decorative elements, thereby improving the fidelity of complex form modeling [14,15]. The stepwise data fusion, supported by rigorous geodetic control (WGS 84/UTM Zone 38N; ICP/SICP), resulted in a metrically coherent composite that supports both authoritative 2D outputs and reality-based 3D models suitable for HBIM integration.

A key contribution of this work lies in the operational integration of GIS thematic mapping with element-level HBIM semantics. Orthorectified façade and roof orthophotos, together with feature-segmented point-cloud derivatives, were organized into categorized GIS layers representing materials, cracks, detachments, deformations, and construction phases. These layers were linked to parametric HBIM elements through shared coordinates and persistent identifiers, enabling traceable and bidirectional queries. This interoperability allowed spatial patterns identified in GIS—such as moisture belts, crack networks, and material detachments—to be localized within HBIM to specific walls, arches, domes, and the minaret, thereby supporting quantitative assessment and monitoring [1,26,31]. In the case of the Great Mosque, the west and north façades exhibited the most severe deterioration. Lateral cracks accounted for approximately 55% and 65% of the documented cracking on these façades, respectively, while moisture-induced decay was prevalent from

the plinth to the mid-wall. Additional cracking was observed around openings and architectural transitions. By embedding these diagnostics as element-level properties, the HBIM model functioned as a decision-support environment that facilitated priority ranking, location-specific intervention planning, and traceable updates across inspection cycles. Two methodological implications for HBIM implementation in historical contexts emerge from this study. First, the limited availability of heritage-specific parametric libraries remains a significant challenge. The development of specialized families at LOD 300 (architectural) and LOD 350 (structurally and diagnostically critical elements) addresses this gap while balancing geometric fidelity and model performance [6,21]. Selective geometric simplification, typically in the range of 10–30%, preserves measured curvature and junction logic while maintaining authoring efficiency. Second, provenance-rich semantic structuring is essential. Systematic documentation of data sources, survey dates, and methodologies within element attributes supports longitudinal updates without repeated remodeling and enables reproducible GIS–HBIM queries. This aspect is particularly critical in conflict-affected and data-scarce environments, where iterative documentation campaigns and incomplete archives are common.

The findings are consistent with international practices in which HBIM–GIS integration accelerates documentation-to-intervention workflows, as demonstrated in major conservation projects such as the Sagrada Familia in Spain and Mosquera Castle in Italy [38]. The distinguishing contribution of the present study lies in its validated applicability under conditions of restricted standoff, limited access, and institutional constraints, which are typical of Yemen and comparable contexts. The reliance on commercially accessible toolchains and defensible alignment strategies, constrained by CP/ChP distributions and ICP/SICP procedures, enhances transferability while maintaining metric rigor across heterogeneous datasets. Despite these achievements, several limitations remain. Multi-source data fusion is inherently sensitive to coverage disparities, radiometric inconsistencies, and heterogeneous point densities. In this study, these issues were mitigated through confidence-based masking, conservative decimation within ICP overlap regions, and explicit topological rules applied in GIS, resulting in stable registrations and coherent thematic layers [63]. Additional challenges stemmed from Yemen’s political instability, limited access to advanced surveying equipment, scarcity of local expertise, and incomplete historical documentation. These constraints were addressed through data triangulation using orthophotos, field notes, and historical imagery, as well as through stakeholder engagement, which supported reliable historical phasing and condition assessment despite documentation gaps. Beyond technical outcomes, the resulting HBIM–GIS assets also support educational dissemination and virtual-access applications, contributing to heritage awareness, urban regeneration initiatives, and tourism revitalization [64].

Overall, this study presents a repeatable and phase-aware HBIM–GIS framework that transforms hybrid survey data into actionable diagnostics. By localizing moisture- and crack-related pathologies to specific architectural elements and quantifying their extent, the approach enables material-compatible and location-specific conservation strategies. Future research should focus on incorporating temporal dimensions through recurrent HBIM–GIS updates to assess intervention effectiveness and degradation trends, as well as on refining ontologies that describe relationships among construction phases, materials, and pathologies to improve cross-site comparability. The proposed framework thus offers a scalable and robust solution for cultural heritage management in resource-limited and conflict-affected settings, aligning with international standards while remaining practical within the operational context of Yemen [38,61,65].

Beyond the specific case of the Great Mosque of Ibb, the findings of this study offer broader insights for digital heritage documentation in conflict-affected and resource-

limited contexts. In such settings, access restrictions, incomplete archives, and limited technical infrastructure often preclude the systematic application of high-cost or equipment-intensive survey methods. The proposed GIS–HBIM framework demonstrates that a carefully designed, image-based workflow can still deliver metrically reliable and semantically rich documentation capable of supporting conservation decision making. In this respect, the study highlights the strategic role of GIS–HBIM integration in structuring a diagnosis–decision–intervention chain: GIS enables the spatial identification and classification of deterioration patterns; HBIM localizes these diagnostics at the element level, quantifies their extent, and links them to material, phase, and provenance information; and the combined environment supports informed, location-specific intervention planning.

The study also underscores important trade-offs between low-cost and high-precision documentation approaches. While laser-scanning-dominant workflows can provide higher geometric density and automation potential, they often require costly equipment, specialized expertise, and stable operational conditions that are difficult to guarantee in conflict-affected regions. By contrast, the hybrid photogrammetric strategy adopted here prioritizes flexibility, accessibility, and reproducibility, while still achieving accuracy sufficient for conservation planning when supported by rigorous geodetic control and quality assurance. Rather than positioning photogrammetry and laser scanning as mutually exclusive, the results suggest that image-based GIS–HBIM workflows offer a pragmatic and scalable alternative—or complement—where constraints limit the deployment of laser scanning, thereby expanding the applicability of digital heritage methods across diverse and challenging operational contexts.

6. Conclusions

This study demonstrates that integrating HBIM and GIS with a hybrid photogrammetric pipeline (TDP, UAVDP, SP) and geodetic control provides a strong, interoperable framework for documenting and conserving complex heritage buildings (HBs) in challenging environments. For the Great Mosque of Ibb, Yemen, this methodology produced a highly accurate 3D model and actionable conservation insights. The staged fusion strategy (UAVDP→TDP via ICP; SP→UAV–TDP via SICP) generated a high-density, georeferenced point cloud (WGS 84/UTM Zone 38N), merging façade-level details with building-wide coverage. The key findings are as follows: Firstly, a parametric HBIM pipeline with a purpose-built library (LOD 300–350), preserving irregular morphology while supporting downstream coordination and material take-offs. Secondly, the GIS thematic mapping program converted diverse data into queryable layers, revealing moisture-induced decay and crack networks, facilitating localized conservation interventions. Thirdly, the data-enrichment framework ensured traceable updates across inspection cycles and supported cross-domain interoperability between GIS and HBIM.

The integration of HBIM and GIS goes beyond inventory-based documentation, enabling a diagnostics-to-action pipeline where spatial patterns identified in GIS are quantified and localized in HBIM, supporting location-specific interventions, restoration estimates, and informed decision making. While the methodology is replicable and adaptable to resource-constrained and conflict-affected contexts, challenges remain, particularly in multi-source data fusion, radiometry, and thematic mapping quality. Future research will focus on strengthening ontology integration to more effectively represent relationships among materials, construction phases, and pathologies. In addition, the incorporation of non-destructive testing techniques and environmental time series is expected to enhance predictive diagnostic capabilities. Finally, the selective application of machine-learning approaches for segmentation and classification may streamline thematic map production while preserving both metric accuracy and operational efficiency. Overall, the proposed

framework offers a scalable, replicable template for proactive conservation of architectural heritage in challenging operational environments, turning hybrid survey data into actionable conservation intelligence.

Author Contributions: B.Q.D.D.: conceptualization, methodology, field investigation, data curation, formal analysis, visualization, writing—original draft, writing, review, and editing. D.J.: conceptualization, supervision, review and editing, validation, resources. A.Q.D.: methodology, data curation, validation, writing, review, and editing. S.A.: review and editing. A.H.: validation, review, and editing. A.B.: conceptualization, supervision, review and editing, validation, resources, project administration. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available from the corresponding author (B.Q.D.D.) upon request.

Conflicts of Interest: The authors state that they have no conflicts of financial interest or personal relationships that could potentially impact the objectivity or integrity of research findings.

Abbreviations

CH	Cultural heritage
HBs	Heritage buildings
TDP	Terrestrial digital photogrammetry
UAVDP	Unmanned aerial vehicle digital photogrammetry
SP	Spherical photogrammetry
PCs/PC	Point cloud/s
HBIM	Heritage Building Information Modeling
GIS	Geographic information systems
LOD	Levels of Development
LoD	Levels of Detail
SC	Semantic Classification

Appendix A

Table A1. The principal structural and spatial components of the mosque.

Main Structure of the Mosque		
	Description	Materials/Construction Details
Courtyard (Sahn)	Central open court at the heart of the complex; plan approx. 19.20 × 13.50 m; surrounded on four sides by arcaded corridors; the Qibla passage is the most prominent, its central bay roofed with a series of elaborately adorned domes; each colonnade opens to the sahn via columns/buttresses with arched openings.	Masonry arcades with columns/buttresses and arches; domed roofing over the central Qibla passage; circulation organized by four continuous corridors.



Table A1. Cont.

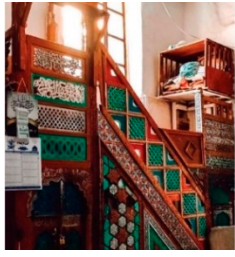
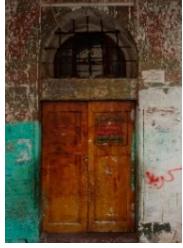
Main Structure of the Mosque		
	Description	Materials/Construction Details
Prayer Hall (Muşallā)	Located on the northern perimeter, opens to the northern gallery overlooking the sahn; three entrances along the southern wall; larger in area than the courtyard.	Load-bearing masonry; interior spans articulated by colonnades; direct visual/functional connection to the sahn through the northern gallery.
		
Mihrabs (2)	Two historic prayer niches are centrally positioned within the northern section of the prayer hall; focal points for the Imam; intricate carvings with Qur'anic verses and decorative inscriptions; layered inscriptions reflect stylistic evolution across eras.	Carved stone/plaster work with calligraphic and vegetal/geometric ornament; stratified epigraphy on intrados and sidewalls.
		
Minbar	Wooden pulpit adjacent to the mihrabs; richly carved inscriptions and geometric patterns; current minbar replaced an older pulpit; stylistic affinities with 5th century A.H. traditions; many components from rare, aged wood.	Fine joinery; high-quality hardwood elements; layered decorative program consistent with historic workshops.
		
Entrances (Doors)	Six main entrances of varying scale/treatment; small auxiliary door near the northern platform; octagonal eastern entrance with domed ceiling as a prominent feature; southern entrance gives direct access to the minaret at the SE corner of the sahn. Two recurrent door types: (a) wooden door topped by a semi-circular upper window for access + lighting; (b) wooden door with decorated panels, topped by a solid semi-circular stone arch plastered.	Primarily two-leaf wooden doors (one operable leaf in use); type (a) integrates fanlight; type (b) integrates plastered stone arch; internal spatial sequence coordinated with circulation to sahn and galleries.
		 

Table A1. Cont.

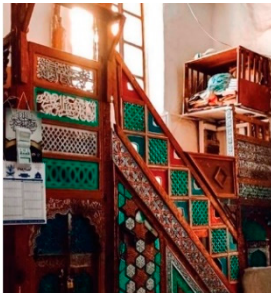
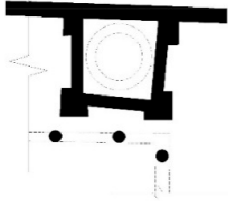
Main Structure of the Mosque			
	Description	Materials/Construction Details	
Windows	Two façade types: (a) semi-circular windows; (b) square windows. Timber frame sits at the inner edge of the opening, leaving wall thickness expressed externally; timber mullions subdivide openings into 9 small lights (semi-circular) and 6 small lights (square); glass panels fitted; external iron mesh for security.	Timber frames and partitions; glazing in small panes; expressed wall reveal externally; protective iron mesh to the exterior face.	
			

Appendix B

Table A2. Architectural elements of the mosque of Ibb.

Architectural Elements			
Element	Typology and Description	Materials/Construction	Significance
Arches	Two families: external arches resembling horseshoe profiles, and interior (courtyard) arches of two styles, horseshoe unit and pointed with angular apex. The Qibla wall is notable for vertical stone slabs acting as symbolic/physical dividers within the prayer space.	Stone piers/columns and buttresses carrying arched spans; coursed masonry with carved imposts in key bays.	Provide structural transfer to upper elements and define rhythmic bays; articulate spatial hierarchy and add interior elegance; Qibla-wall slabs are an unusual Yemeni feature with liturgical resonance.
Ornaments (Interior)	Intricate geometric patterns, floral motifs, and celestial symbols (planets, six-pointed stars) adorn walls and ceilings.	Carved/plastered decoration; painted or incised motifs integrated with surface finishes.	Encodes layers of artistic tradition; enriches liturgical ambiance; evidences stylistic evolution across historical eras.
Ornaments (Minaret)	Decorative carvings and patterned bands embellish the minaret exterior.	Plaster inscriptions and relief work applied over masonry.	Distinctive landmarking of the tower reinforces the mosque’s visual identity in the urban skyline.

Table A2. Cont.

Architectural Elements				
Element	Typology and Description	Materials/Construction	Significance	
Merlons	Triangular crowning elements are gradually inscribed on both sides, defining the roofline.	Stone merlons coated with gypsum.	Accentuate the silhouette; provide a characteristic Yemeni upper profile and weathering edge.	
Domes (16 total)	Clustered in the northern section, small domes on circular bases; the large central dome on a polygonal base; interiors carry distinctive decorative programs.	Local stone and limestone construction; distinctive decorative elements on the interior; curved shells rising from base rings.	Among the oldest Yemeni mosque domes, they distribute loads efficiently and resist environmental forces; define the prayer space canopy.	
Woodwork	Ornamental carpentry across doors, windows, mihrabs, and the minbar; dense repertoire of geometric, calligraphic, and floral motifs; some components in rare, aged woods.	Traditional Yemeni joinery: paneled leaves, fanlights, mullions; fine carving and inlay consistent with historic workshops.	Contributes to both esthetics and function (light, ventilation, thresholds); emblematic of local craftsmanship; deterioration risk from moisture warrants focused conservation.	
Minarah (Spire)	Octagonal-plan tower at the SE corner of the sahn; composed of four sections: rectangular base, polygonal superstructure with plaster inscriptions, gallery balcony, and pyramidal pinnacle surmounted by a small white dome; eastern door to balcony; internal stair. Height ≈ 25 m; an inscription (685 A.H./1286 C.E.) attributes construction to Asad al-Hasan b. Shams al-Din b. 'Ali b. Rasul.	Masonry core with refined geometric brickwork; plastered inscriptional bands; timber thresholds/doors.	Powerful Islamic symbol (adhan); key urban way-finding element; stratified epigraphy underscores deep historical roots and high craftsmanship.	 

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