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Advanced digital technologies for heritage surveying: Unmanned aerial vehicle photogrammetry, laser scanning, and heritage building information modeling for the Onufri Museum

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Abstract

Reliable digital recording and analytical interpretation of architecturally complex historic monuments remain challenging, particularly for structures with irregular geometries, stratified construction, and seismic vulnerability. While unmanned aerial vehicle (UAV) photogrammetry, terrestrial laser scanning, and heritage building information modeling (HBIM) have been widely applied in isolation, their integrated use as a coherent, research-driven workflow remains insufficiently explored for Orthodox ecclesiastical museums embedded in dense historic fabrics. To address this gap, we develop and validate a hybrid digital survey methodology combining UAV-based photogrammetry, mobile light detection and ranging, and point-cloud-driven HBIM, applied to the Onufri National Museum in Berat, Albania, a United Nations Educational, Scientific, and Cultural Organization World Heritage context. High-density datasets were processed and converted into a geometrically rigorous HBIM model, enabling the identification of previously undocumented spatial irregularities, dome asymmetries, and constructional hierarchies that are absent from existing archival documentation. The results demonstrate that the proposed workflow achieves sub-centimetric to centrimetric geometric consistency across most elements, significantly improving spatial completeness, modeling reliability, and diagnostic potential compared to conventional survey approaches. Beyond documentation, the HBIM environment functions as an analytical interface for structural interpretation, pathology mapping, and future conservation planning. By foregrounding measurable outcomes and methodological transferability, the study contributes a replicable digital documentation framework applicable to complex heritage buildings in seismic and constrained urban contexts, reinforcing the role of integrated HBIM as a scientific instrument rather than a representational tool in heritage conservation research.

Keywords: Architectural documentation; Digital surveying techniques; Unmanned aerial vehicle photogrammetry; Technology; Cultural preservation

1. Introduction

The rapid digitalization of cultural heritage documentation over the last decade has fundamentally reshaped research priorities in heritage science. Comprehensive international reviews consistently indicate a shift from descriptive digitization toward data-driven analytical frameworks capable of supporting conservation decision-making, structural assessment, and risk evaluation.[1–4] However, despite significant technological advancement in reality capture systems, a persistent methodological gap remains between high-density data acquisition and scientifically validated interpretation.[1,2,4] Recent bibliometric analyses show that research on heritage building information modeling (HBIM), digital twin, and Internet of Things is converging, highlighting emerging methodological frontiers beyond traditional scan-to-building information modeling (BIM) workflows.[5] This gap has prompted renewed scrutiny of how digital models are constructed, verified, and epistemologically grounded within heritage research.

Historic architectural heritage represents a critical field for the advancement of digital documentation methodologies, not merely due to its geometric complexity, but because of the epistemological challenge of translating irregular, stratified, and often deformed physical realities into verifiable digital knowledge. Unlike new construction, heritage buildings embody cumulative construction phases, material aging, seismic adaptations, and non-standardized geometries that resist idealized representation and challenge conventional survey abstraction.[1,4,6] Systematic reviews underline that HBIM research increasingly focuses on semantic enrichment, digital twin integration, and conservation-oriented analytical frameworks, reflecting the field's evolution beyond purely descriptive approaches.[7,8] Large-scale review analyses further note that irregular geometries, material decay, and undocumented structural interventions introduce systematic uncertainty in digital modeling processes, often exceeding the tolerance assumptions embedded in conventional BIM standards.[1,3,4] Consequently, the reliability of heritage digital models depends not only on geometric density, but also transparent validation protocols capable of quantifying deviation and modeling bias.[1,4,9,10]

Over the last two decades, digital surveying technologies, particularly unmanned aerial vehicle (UAV) photogrammetry, terrestrial and mobile light detection and ranging (LiDAR) scanning, and HBIM have profoundly transformed heritage documentation practices. However, while the technical capacity for high-density data acquisition has expanded rapidly, the scientific interpretation of such data within coherent analytical frameworks has not progressed at the same pace.[4–6] As highlighted in several state-of-the-art reviews, digital heritage workflows often prioritize visual output and representational completeness, while underutilizing the potential of integrated models for structural understanding, diagnostic reasoning, and conservation decision support.[1,2,6]

The HBIM was introduced as a methodological framework designed to integrate geometric accuracy, historical stratification, and material knowledge within a single digital environment, explicitly aimed at overcoming challenges posed by irregular, deformed, and stratified historic architectures.[3,4,6] Unlike conventional BIM, HBIM emphasizes traceability between survey data and parametric interpretation, facilitating systematic detection of deviations between as-built conditions and modeled elements.[1,2,8,11,12]

Recent studies highlight three critical methodological challenges: (i) integration of heterogeneous survey datasets without loss of metric fidelity, (ii) preservation of geometric accuracy during scan-to-BIM conversion, and (iii) validation of HBIM as an analytical tool for structural and conservation assessment rather than mere visualization.[2,4,6] These challenges are particularly acute in Orthodox ecclesiastical heritage, where hybrid masonry-timber systems, non-orthogonal geometries, and seismic vulnerabilities complicate both acquisition and modeling.[13–15]

Against this backdrop, the present study addresses a critical research gap: While hybrid survey approaches are widely advocated in review literature, few studies systematically evaluate their geometric coherence within a unified HBIM validation framework. Even fewer examine how point-cloud-driven parametric modeling can serve as an instrument for structural interpretation rather than as a visualization pipeline.[2–4] This unresolved methodological tension defines the core research gap addressed in this study.

The research is guided by three interrelated questions: (i) How can integrated multi-source survey strategies overcome occlusion and accessibility constraints in dense historic fabrics?[9,16,17] (ii) To what extent can point-cloud-driven HBIM generate verifiable geometric and structural knowledge absent from archival documentation?[1,4] (iii) How transferable is such a methodology to comparable heritage contexts characterized by irregular geometry and structural complexity?[6,18] Recent methodological reviews argue that these challenges persist largely due to the absence of standardized integration pipelines, explicit accuracy thresholds, and reproducible validation frameworks across case studies.[1,2,4] In particular, scan-to-BIM transitions frequently rely on expert-driven modeling decisions that remain insufficiently documented, limiting methodological transferability and comparative assessment.[1,7,9,10,12]

By positioning HBIM as an analytical and epistemic framework rather than a technical end product, this study contributes a validated, research-oriented workflow that bridges digital acquisition and conservation-oriented interpretation.

2. State-of-the-art analyses and research background

The evolution of digital heritage documentation has been extensively examined in recent international review literature, which collectively identifies HBIM as a pivotal methodological paradigm in heritage science. Unlike traditional computer-aided design (CAD)-based documentation, HBIM is conceived as a data-driven environment that integrates geometry, semantics, and analytical interpretation within a single digital framework.[1,4–6,8] Authoritative review studies consistently emphasize that the defining challenge of HBIM lies not in data acquisition, but in the epistemological translation of imperfect, deformed, and historically stratified architecture into parametric representations without compromising geometric truth.[4,6] Pocobelli *et al.*[6] underline that heritage BIM must operate under fundamentally different assumptions than contemporary BIM, as historic buildings lack standardized components, exhibit construction irregularities, and embody temporal transformation.

Recent experimental studies have begun quantifying this translation gap through deviation mapping, cloud-to-model comparison metrics, and tolerance threshold analysis, revealing discrepancies that often exceed conventional BIM standards in irregular masonry contexts.[8] These findings suggest that HBIM reliability depends not only on modeling skill, but also on explicit validation protocols capable of measuring geometric drift between surveyed data and parametric abstraction.[8,11]

Early theoretical foundations articulated by Arayici *et al.*[3] framed HBIM as a knowledge integration system rather than a modeling technique, highlighting the need for transparency, data provenance, and interpretative accountability. Subsequent reviews expanded this framework, identifying scan-to-BIM workflows as a critical yet problematic interface where loss of geometric fidelity frequently occurs.[1,4] Critical reviews also emphasize that HBIM should combine geometric precision with semantic and historical data to inform conservation decision-making and risk management.[7,12]

Recent state-of-the-art analyses converge on the concept of the digital twin for cultural heritage, emphasizing dynamic, multi-source, and analytically enriched digital representations.[2,6] However, Dang *et al.*[2] demonstrate that numerous heritage digital twin implementations remain nominal, lacking the geometric rigor and validation protocols required for structural analysis or conservation planning. These reviews stress that high-fidelity geometry derived from integrated survey strategies is a prerequisite, not a by-product of analytical HBIM and digital twin development.

Within this context, UAV photogrammetry and LiDAR scanning have emerged as complementary acquisition technologies. Photogrammetry offers high-resolution surface reconstruction and chromatic detail, while LiDAR provides robust metric accuracy and volumetric completeness under challenging lighting and spatial conditions.[17–19] Literature consistently advocates hybrid acquisition strategies, yet also notes the absence of standardized integration and validation procedures across heritage applications.[4,11,12,16]

Critically, multiple reviews identify ecclesiastical and masonry-dominated heritage as underexplored domains in HBIM research, despite their structural complexity and conservation sensitivity.[6,13,15] Orthodox churches, in particular, exhibit hybrid masonry–timber systems, non-orthogonal geometries, and incremental construction phases that challenge both survey accuracy and parametric abstraction.

Another recurring limitation highlighted in the literature concerns the ambiguous definition of model detail, accuracy thresholds, and semantic completeness in HBIM. Unlike contemporary BIM, heritage modeling lacks universally accepted criteria for validating geometric reliability and interpretive consistency, complicating reproducibility and comparative assessment.[1,4,5,8]

In response to these gaps, the present study aligns with recent calls for research-oriented HBIM methodologies grounded in integrated survey validation, geometric transparency, and analytical accountability. By applying a hybrid UAV-LiDAR-HBIM workflow to a complex Orthodox iconographic museum embedded in a dense United Nations Educational, Scientific, and Cultural Organization (UNESCO) context, the research directly addresses limitations identified in the current study and advances HBIM practice from descriptive modeling toward scientific interpretation.

3. Case study context: The Onufri National Museum

The Onufri National Museum is located within the fortified urban fabric of Berat Castle, Albania, a UNESCO World Heritage Site characterized by dense historical stratification, complex topography, and continuous habitation (Figure 1). The museum occupies the former Cathedral of the Dormition of St. Mary, an Orthodox ecclesiastical building originally constructed in 1797 on the foundations of an earlier sanctuary, and represents one of the most architecturally and culturally significant monuments within the castle ensemble.[14,20]

From an architectural perspective, the building exemplifies late Byzantine and Ottoman-period ecclesiastical construction practices adapted to local conditions. Its spatial configuration comprises a naos, narthex, lobby, and attached side chambers, articulated through irregular volumes and non-orthogonal geometries dictated by both liturgical requirements and the sloping terrain. The church was historically integrated into a larger metropolitan complex, of which only the cathedral structure has survived, further increasing its architectural and documentary value.[13,15] The museum takes its name from Onufri, the celebrated 16th-century Albanian master of iconography and fresco painting.

The museum functions today as Albania's principal repository of Orthodox iconographic heritage, preserving a curated collection of 173 objects selected from a wider fund exceeding 1,200 artifacts originating from

Figure 1. Berat Castle. (A) Location of the Onufri National Museum. (B) Archival images of the building.
Source: Archive of the Regional Directorate of Cultural Heritage (DRTK), Berat, Albania. https://drtkberat.gov.al/.

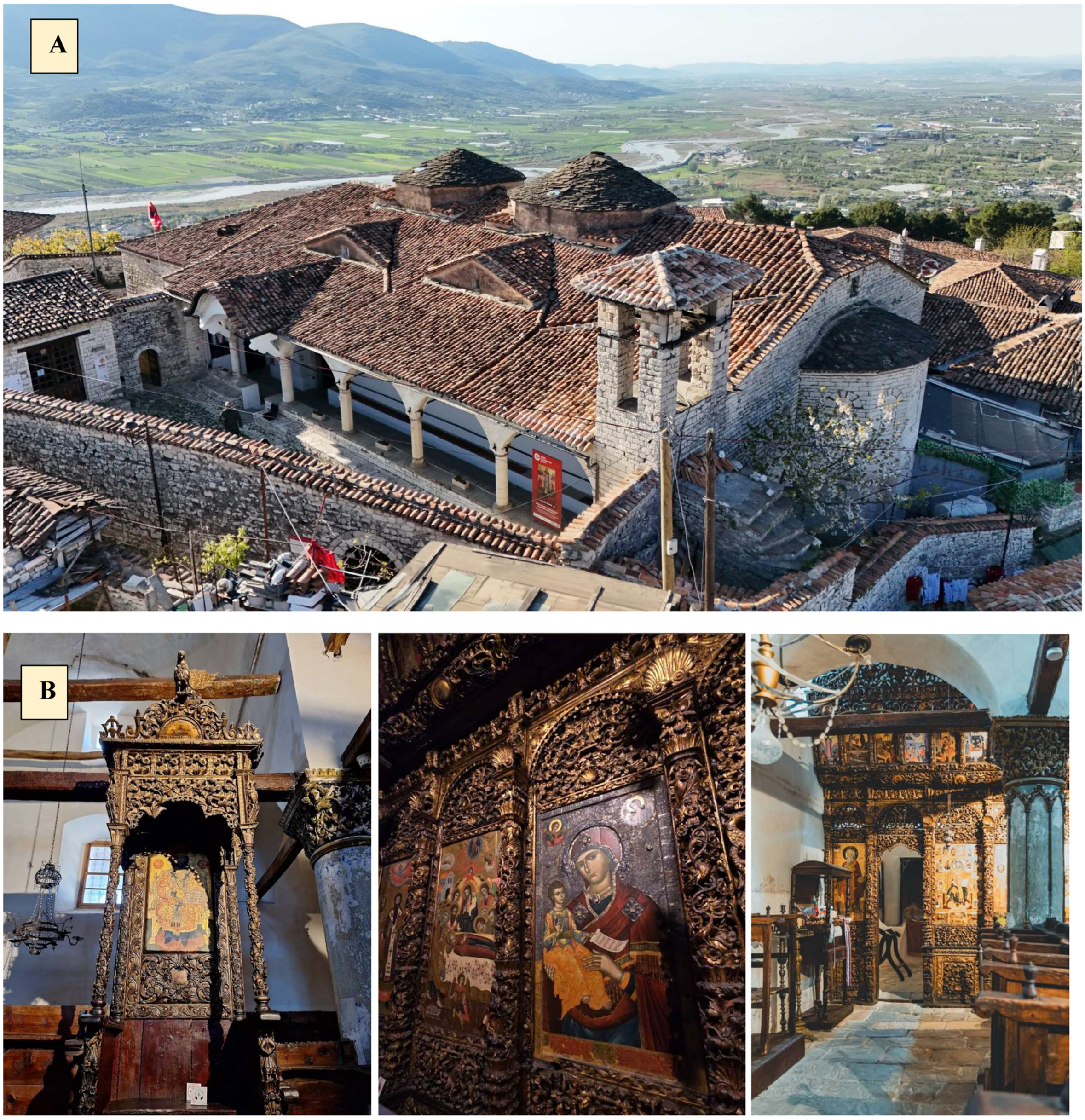

Figure 2. Main views of the building under study. (A) Exterior image of the museum captured by drone. (B) Interior photos captured during site visit.

churches and monasteries across the country (Figure 2). These include icons dating from the fourteenth to the early twentieth century, attributed to Onufri, Nikolla Onufri, David Selenica, Kostandin Shpataraku, and other prominent Albanian iconographers, as well as finely crafted liturgical objects signed by local silversmiths.[15] Of exceptional international significance are the Codex Purpureus Beratinus and the Codex Aureus Anthimi, both inscribed in UNESCO's "Memory of the World" register and preserved beneath the cathedral apse.[20]

The museum functions today as Albania's principal repository of Orthodox iconographic heritage, preserving a curated collection of 173 objects selected from a wider fund exceeding 1,200 artifacts originating from churches and monasteries across the country. These include icons dating from the fourteenth to the early twentieth century, attributed to Onufri, Nikolla Onufri, David Selenica, Kostandin Shpataraku, and other prominent Albanian iconographers, as well as finely crafted liturgical objects signed by local silversmiths.[15] Of exceptional international significance are the Codex Purpureus Beratinus and the Codex Aureus Anthimi, both inscribed in UNESCO's

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Architecturally, the monument is distinguished by a hybrid structural system that combines massive stone masonry walls, a regular grid of interior stone columns with carved capitals, and a layered roofing assembly composed of masonry domes and a timber truss structure supporting ceramic tiles. The roof system includes two principal domes of differing diameters and geometric characteristics, as well as smaller domes above the altar area, reflecting successive construction phases and structural adaptations over time.[14] Such hybrid masonry timber configurations are typical of ecclesiastical architecture in the Balkan region but pose significant challenges for accurate geometric documentation and structural interpretation. The museum complex further includes a later, two-story exhibition wing constructed in the late twentieth century to accommodate museological functions. Although architecturally subordinate to the historic church, this addition is physically connected to the cathedral volume and contributes to the overall spatial and functional system of the site. The interface between the historic structure and the modern extension introduces additional geometric complexity and requires careful documentation to ensure continuity between conservation, management, and future adaptation strategies.

From a documentation standpoint, the Onufri National Museum presents a set of conditions that make it particularly suitable as a case study for advanced digital surveying research. These include restricted accessibility due to adjacent historic buildings, limited visibility of certain façades, irregular volumetric relationships, and the presence of delicate artistic and architectural elements that preclude invasive investigation methods. Moreover, the monument is situated within a seismically active region, where precise knowledge of geometry, deformation, and structural hierarchy is essential for informed conservation planning.[15,21] For these reasons, the Onufri National Museum is not treated in this study merely as an object of documentation, but as an analytical testbed for evaluating the capacity of integrated UAV photogrammetry, mobile LiDAR, and point-cloud driven HBIM workflows to generate reliable, verifiable, and transferable knowledge in complex heritage contexts. The architectural and cultural specificity of the site thus provides the necessary framework within which the methodological and analytical contributions of the research can be rigorously assessed.

4. Materials and methods

4.1. Research design and survey strategy

Our study adopted a structured, multi-scalar survey strategy designed to ensure geometric accuracy, spatial completeness, and analytical reliability in a complex heritage context. The methodological framework integrates UAV-based photogrammetry, mobile LiDAR scanning, and point-cloud-driven HBIM within a unified workflow, enabling cross-validation across heterogeneous datasets and minimizing the limitations inherent to any single acquisition technique.[9,16–18]

The Onufri National Museum presents restricted accessibility, occluded façades, and irregular volumetric articulation due to adjacent historic constructions and sloping terrain. These constraints informed the selection of complementary survey methods and guided the sequencing of data acquisition, ensuring both interior and exterior continuity while avoiding invasive or physically intrusive operations.[14,20]

4.2. Unmanned aerial vehicle-based photogrammetry

Aerial photogrammetric data were acquired using a UAV (Mavic 3E, SZ DJI Technology Co., Ltd., China), selected for its high-resolution imaging capabilities and stability in confined urban environments. Two complete flight campaigns were conducted under stable lighting and weather conditions, capturing approximately 2,100 images in orthogonal and oblique orientations to ensure sufficient overlap and coverage of roofs, façades, and upper structural elements.[17,18]

Image processing was performed using Agisoft Metashape (Version 1.8.5, Agisoft LLC, Russia), following a high-accuracy workflow that included camera alignment, dense point-cloud generation, and orthomosaic production (Figure 2). While photogrammetry provided comprehensive surface coverage and chromatic information, its limitations in capturing narrow interstitial spaces and shaded interior zones necessitated integration with terrestrial LiDAR datasets.[16,19]

4.3. Mobile light detection and ranging survey

To address photogrammetric occlusions and ensure precise capture of interior volumes and concealed façades, a moaign was conducted using the LiDAR scanner (FJD™ Trion P1, FJDynamics, China). This device integrates simultaneous localization and mapping technology, enabling continuous acquisition along complex trajectories without reliance on fixed targets or tripods.[9,17,19]

The scanner operates with a 360° × 270° field of view and a data acquisition rate of approximately 320,000 points per second, achieving a relative geometric accuracy of approximately 1.5–2.0 cm under heritage survey conditions (Figure 3). Exterior scanning required approximately six

Figure 3. Fieldwork images captured during the metric survey. (A) On-site handheld scanning using an FJD Trion scanner. (B) Students' site works using a scanner-meter to measure the interior geometric data of the church. (C) On-site leveling measurements by students. (D) Dimensions sketches were made on-site during the metric survey process.

minutes and generated over 17 million points, whereas interior acquisition was completed in approximately eight minutes, producing an additional 11 million points. Real-time visualization enabled immediate verification of coverage and data consistency on-site.[17,19]

4.4. Point cloud processing and data integration

Photogrammetric and LiDAR datasets were registered within a unified spatial reference system using a hybrid alignment strategy combining common feature identification and iterative closest point refinement. This approach ensured geometric coherence between interior and exterior datasets and allowed mutual validation of positional accuracy (Figure 4).[16,17]

Prior to HBIM integration, point clouds underwent a standardized pre-processing pipeline that included noise filtering, statistical outlier removal, density assessment, and segmentation. Registration quality was evaluated using residual error analysis, with tolerance thresholds appropriate for heritage documentation and parametric modeling workflows.[19]

4.5. Heritage building information modeling criteria and validation

Processed point clouds were imported into Autodesk ReCap Pro (Student version 2025, Autodesk, Inc., United States) and subsequently referenced within Autodesk Revit (Student version 2025, Autodesk, Inc., United States) for HBIM development. A point-to-model workflow was adopted, prioritizing manual parametric construction over automated reconstruction to preserve geometric fidelity and interpretative transparency in the presence of irregular morphologies.[1,17,21]

Architectural and structural elements, including masonry walls, columns, domes, vaults, timber trusses, and roofing systems, were modeled as discrete parametric entities using custom families and adaptive components where standard parametric tools proved insufficient (Figure 5). Modeling accuracy was continuously verified against point-cloud sections, ensuring traceability between source data and HBIM elements.[1,19]

4.6. Methodological scope and limitations

Although the resulting HBIM model achieved high geometric resolution and supported diagnostic interpretation, it did not yet constitute a fully semantic Level of Development 500 model. Material stratification, construction-phase attribution, and performance metadata were partially implemented and required further development through archival integration, non-destructive testing (NDT), and extended parameterization.[1,21]

Acknowledging these limitations is essential to maintaining methodological transparency and avoiding overstatement of analytical capability. The adopted workflow was therefore positioned as a validated geometric and structural foundation for future conservation-oriented applications rather than a definitive digital twin in the strictest sense.[17,19]

5. Results

The results are organized to reflect a progressive analytical

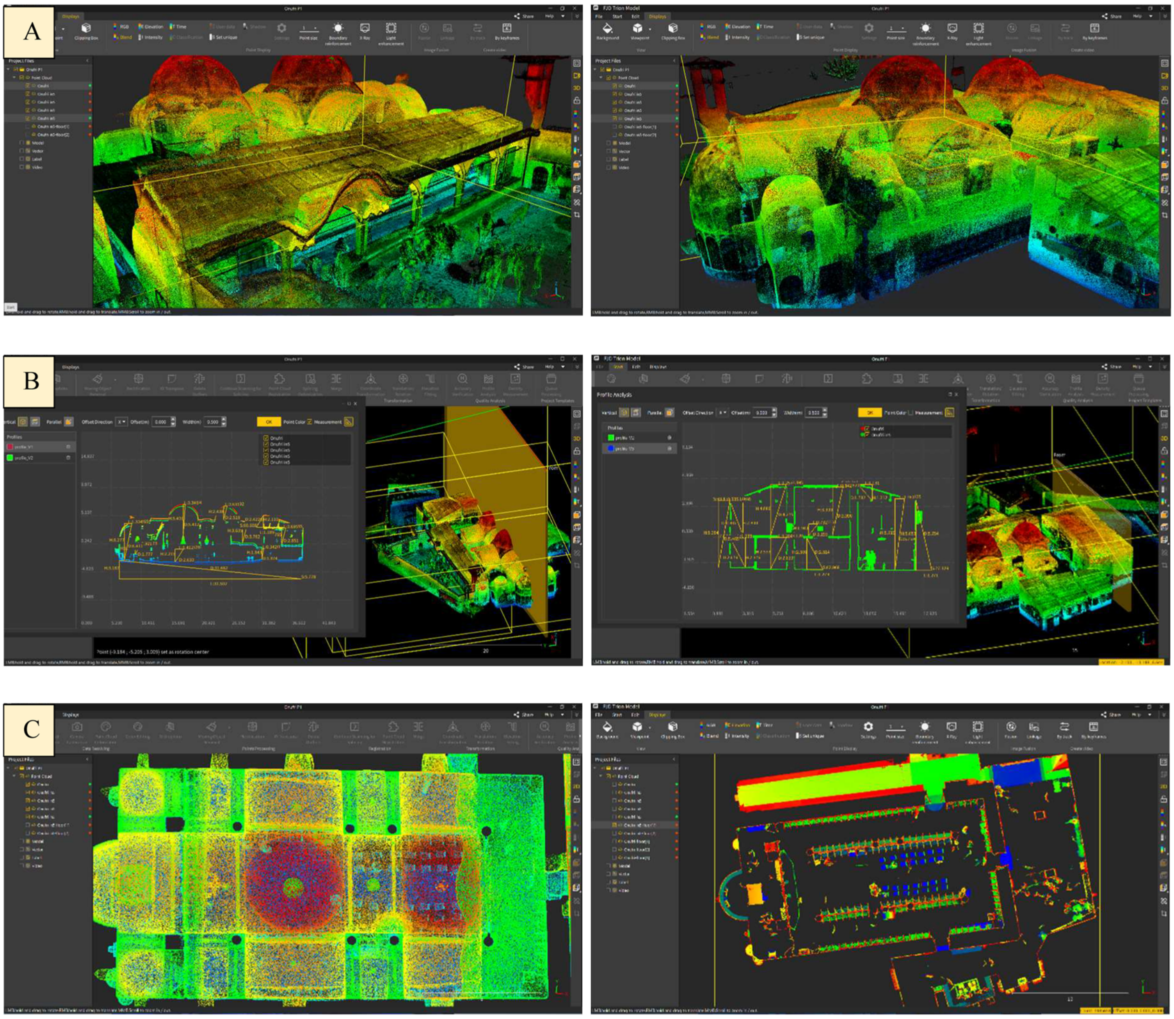

Figure 4. 3D point cloud processing after laser scanning. (A) Three-dimensional point cloud during processing (left), accompanied by a dense cloud (right) to capture the complex forms and volumes of the church interior in FJD Trion software. (B) Automated generation of a section cut of the church. (C) Base plan generation combined with the extraction of the structural plan of the church.

logic, moving from survey completeness and metric accuracy (Sections 5.1 and 5.3) to the identification of geometric irregularities and deformation patterns (Section 5.2) and finally to structural interpretation and diagnostic correlation within the HBIM environment (Sections 5.4 and 5.5). This highlights the interdependence between acquisition accuracy, geometric interpretation, and conservation-oriented analysis.

5.1. Geometric completeness and spatial reconstruction

The integrated photogrammetric and mobile LiDAR survey resulted in a geometrically complete three-dimensional reconstruction of the Onufri National Museum, encompassing exterior façades, roofing systems, interior volumes, and transitional spaces previously undocumented in archival drawings. The hybrid dataset eliminated data gaps caused by occlusions and restricted access, achieving full spatial continuity between the church interior and exterior envelope.[16,17]

Compared to existing two-dimensional documentation, the resulting model revealed discrepancies in wall alignment, column spacing, and roof geometry that could not be reliably detected through conventional survey methods (Figure 6). These findings confirm the effectiveness of integrated point-cloud acquisition in capturing the true as-built condition of complex heritage structures.[18,19]

5.2. Identification of irregular geometries and structural asymmetries

One of the most significant outcomes of the HBIM-based

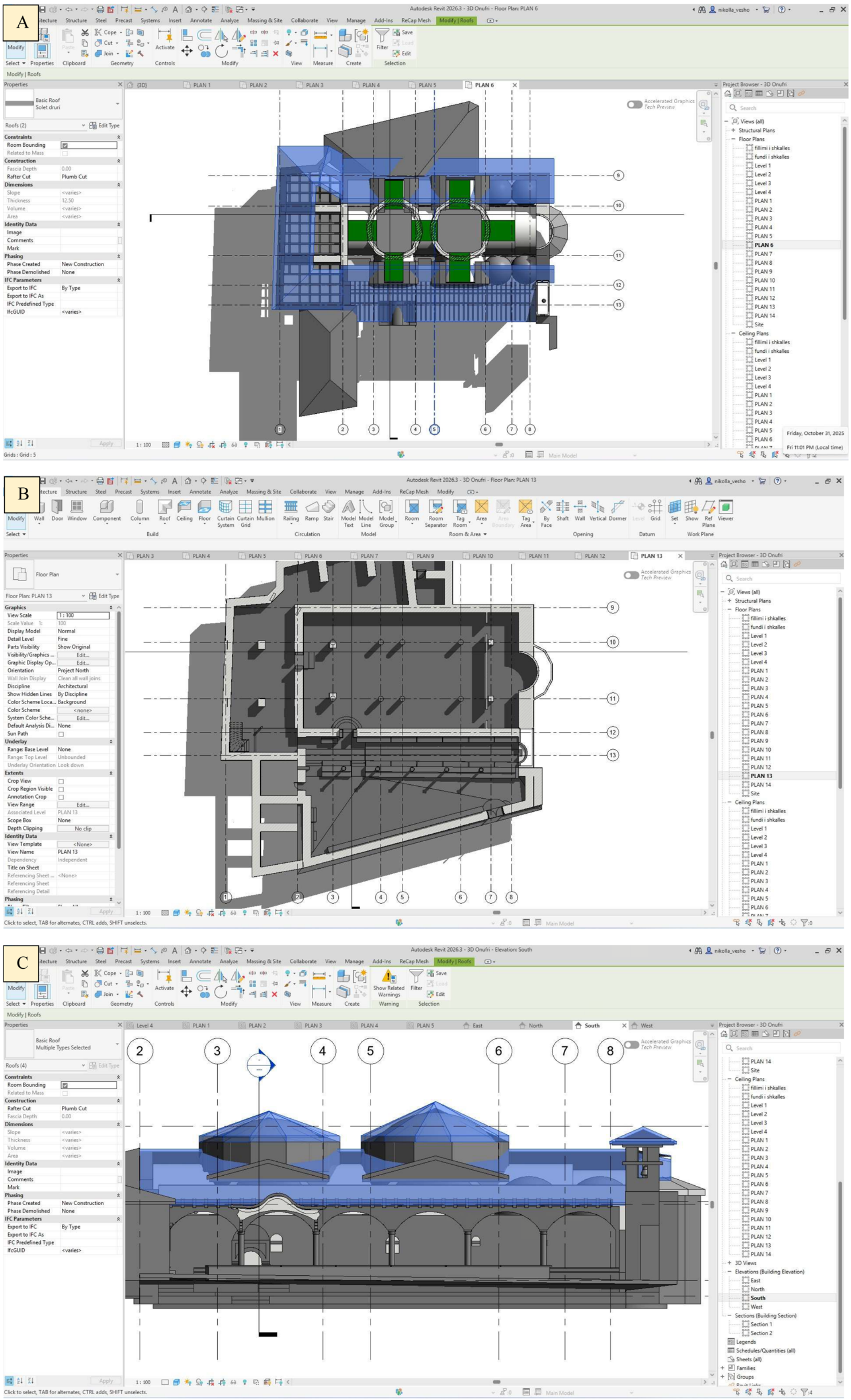

Figure 5. Detailed building information modeling (BIM) in Autodesk Revit. (A) Geometric reconstruction of the roof structure derived from FJD Trion point-cloud data. (B) Extraction of the floor plan at +1.5 m level and structural layout analysis within the BIM environment. (C) Generation of the principal façade and portico elements through parametric modeling and elevation development in Autodesk Revit.

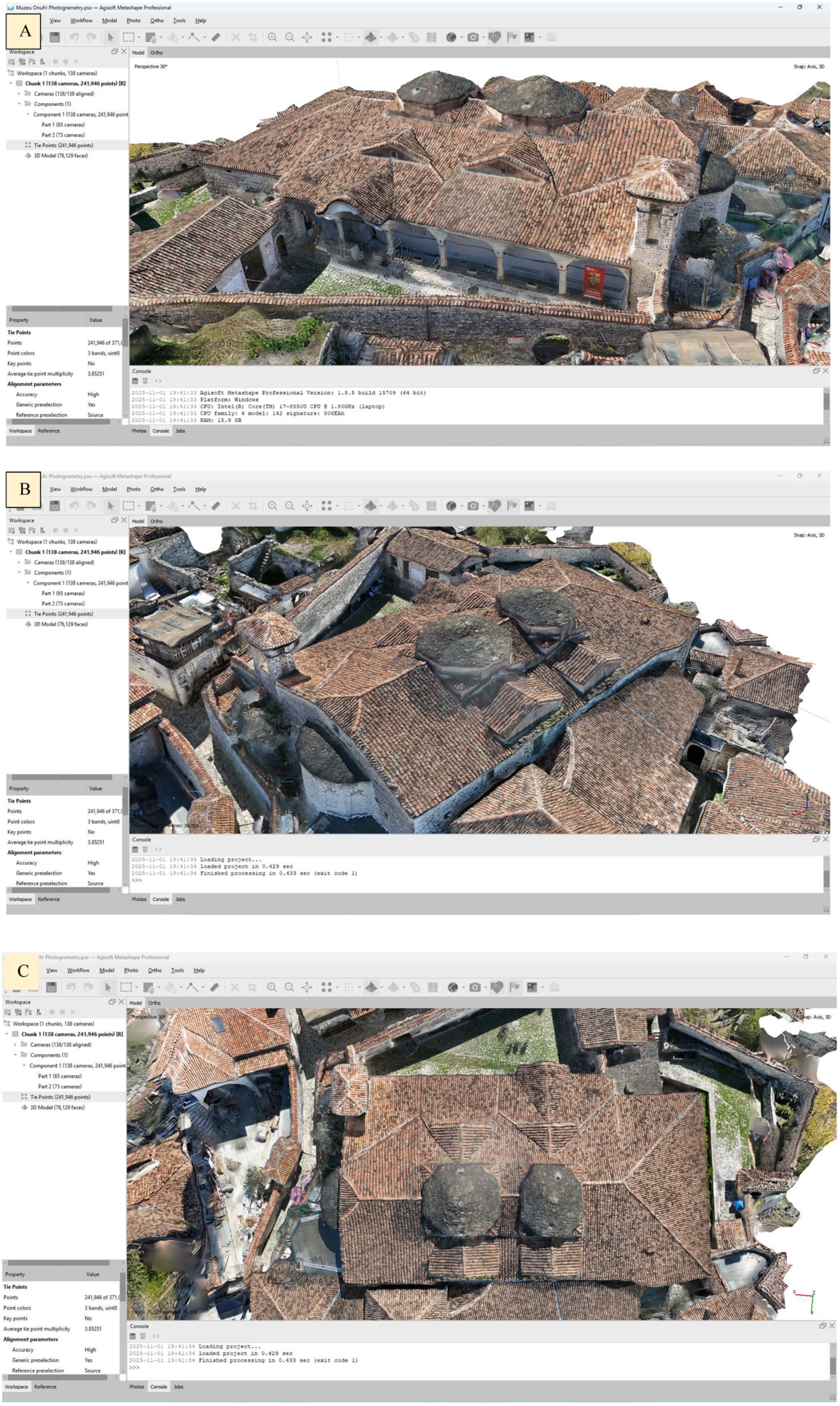

Figure 6. Textured three-dimensional model and diffuse map of the Onufri Museum generated in Agisoft Metashape. (A) Dense point cloud reconstruction highlighting the main portico and façade articulation of the church. (B) Rear-view model illustrating volumetric relationships and spatial interaction with adjacent built structures. (C) Orthomosaic rendering of the overall layout, providing a detailed visualization of the roof geometry and building footprint boundary.

analysis was the identification of previously undocumented geometric irregularities in the dome system. Cross-sectional analysis revealed that the first dome exhibits a measurable elliptical deformation, with deviations exceeding acceptable symmetry thresholds for historic masonry domes, whereas the central dome maintains a near-perfect hemispherical geometry.[17,21]

These asymmetries were not discernible in historical drawings or prior survey records and suggest differentiated structural behavior likely linked to construction phases, material aging, or load redistribution mechanisms (Figure 4). The capacity to extract and compare precise dome profiles directly from the HBIM model constitutes a substantial advancement in the diagnostic understanding of the monument.[14] These geometric findings provide the basis for the structural interpretation and pathology correlation discussed in Sections 5.4 and 5.5.

5.3. Quantitative accuracy and survey performance

Accuracy assessment of the integrated dataset demonstrated sub-centimetric to centimetric consistency across the majority of architectural elements. Registration residuals remained within tolerance ranges appropriate for conservation-grade documentation, confirming the reliability of the hybrid UAV-LiDAR approach.[17,19]

Compared to traditional manual survey techniques, the digital workflow significantly improved both precision and efficiency. Acquisition time was reduced by approximately 60–70%, while geometric resolution increased by an order of magnitude, enabling detailed verification of non-orthogonal walls, warped surfaces, and subtle deformation patterns that are otherwise imperceptible through manual measurement methods (Figure 7).[9,16]

5.4. Heritage building information modeling-based structural interpretation

The translation of point-cloud data into a parametric HBIM environment enabled systematic analysis of structural hierarchies and load-transfer mechanisms. Modeling of columns, capitals, arches, and dome drums as discrete parametric entities clarified the vertical and horizontal relationships governing thrust distribution and structural stability.[1,21]

The HBIM model revealed that stone capitals play a critical mediating role between arches and dome drums, while the timber truss system beneath the roof contributes to horizontal load redistribution. These relationships, although inherent to the building's construction logic, had not been explicitly documented or analytically visualized prior to this study.[14]

5.5. Pathology mapping and diagnostic correlation

The HBIM environment further enabled spatial annotation of material degradation and structural pathologies, including crack patterns, surface detachments, and deformation traces. Notably, fine fissures were observed to correspond spatially with the elliptical deformation of the first dome, suggesting a correlation between geometric distortion and material stress concentration.[21]

Conversely, the central dome exhibited neither significant geometric distortion nor comparable crack propagation, reinforcing the diagnostic value of geometric comparison as a proxy for structural assessment. These correlations demonstrate how HBIM can serve as an analytical interface that links geometry, pathology, and structural behavior (Figure 8).[17]

5.6. Interpretative visualization and model validation

Rendered outputs from the validated HBIM model were used to verify spatial coherence and geometric accuracy rather than serve as analytical evidence. These visualizations confirmed the fidelity of interior–exterior relationships and the overall integrity of the reconstructed museum spaces.[1]

Integration into Autodesk Revit-TwinMotion enabled high-fidelity, real-time renderings and walkthroughs, enhancing interpretive clarity and supporting assessment of spatial hierarchies, material articulation, and lighting conditions (Figure 9). This workflow also lays the groundwork for virtual reality and augmented reality applications, allowing curators, conservators, and the public to explore the museum digitally, supporting education, exhibition planning, and scenario-based analysis without physical intervention.

Comparative inspection against point-cloud data validated both geometric accuracy and visual coherence. By bridging precise reconstruction with immersive visualization, the HBIM model establishes a versatile platform for conservation, interpretation, and public engagement, reflecting contemporary best practices in heritage digitalization.[1,17]

6. Discussion

This study confirms that integrating UAV-based photogrammetry, mobile LiDAR, and point-cloud-driven HBIM enhances geometric validity and supports analytical interpretation in heritage documentation. This section focuses on methodological impact, reliability, and transferability.

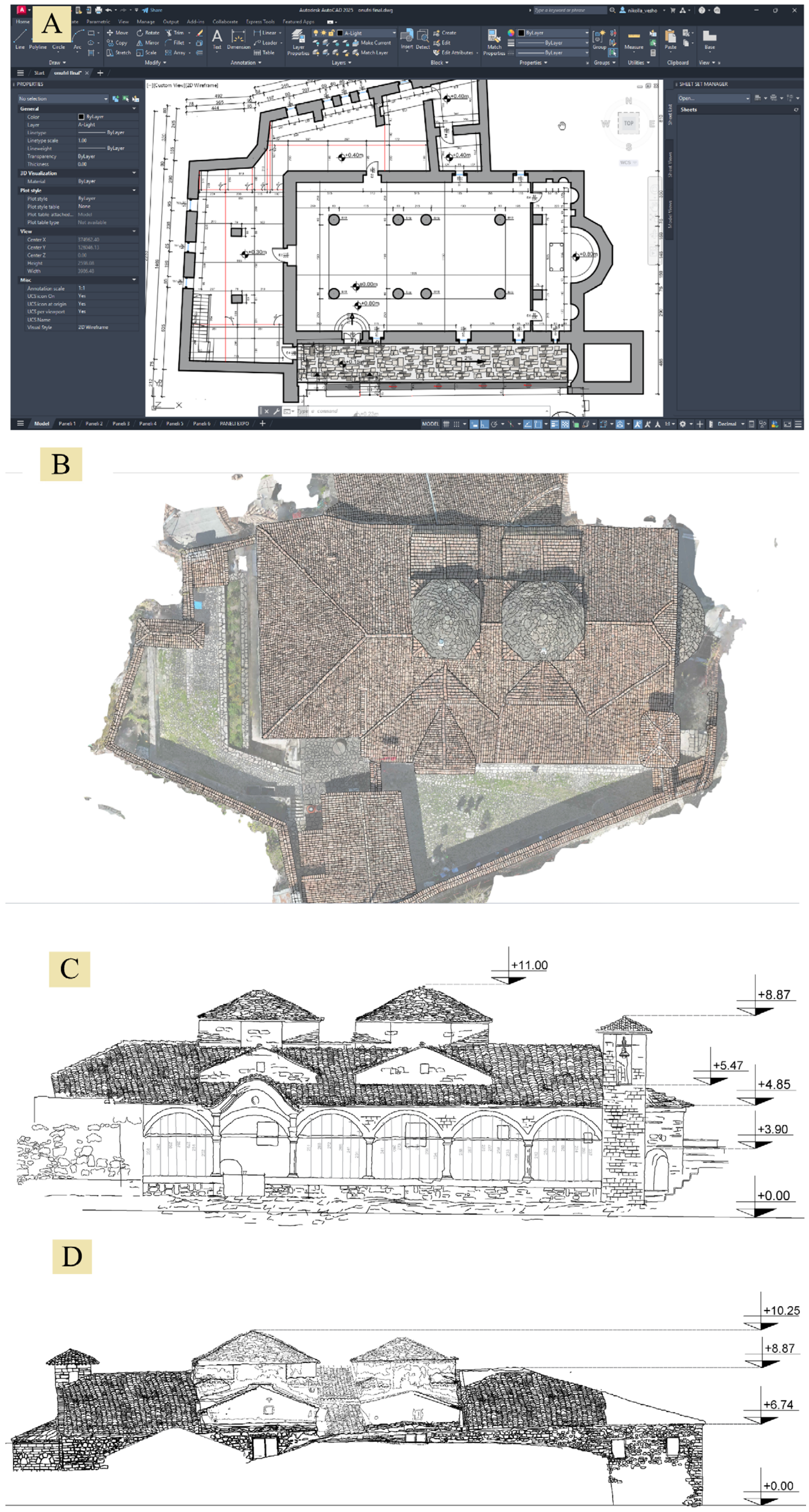

Figure 7. Detailed CAD-based sketches and processing. (A) Digitized planimetry developed in the AutoCAD environment; (B) orthophoto image generated in Agisoft Metashape and manually refined in AutoCAD; (C) southern façade during processing in AutoCAD; (D) northern façade during CAD-based processing.

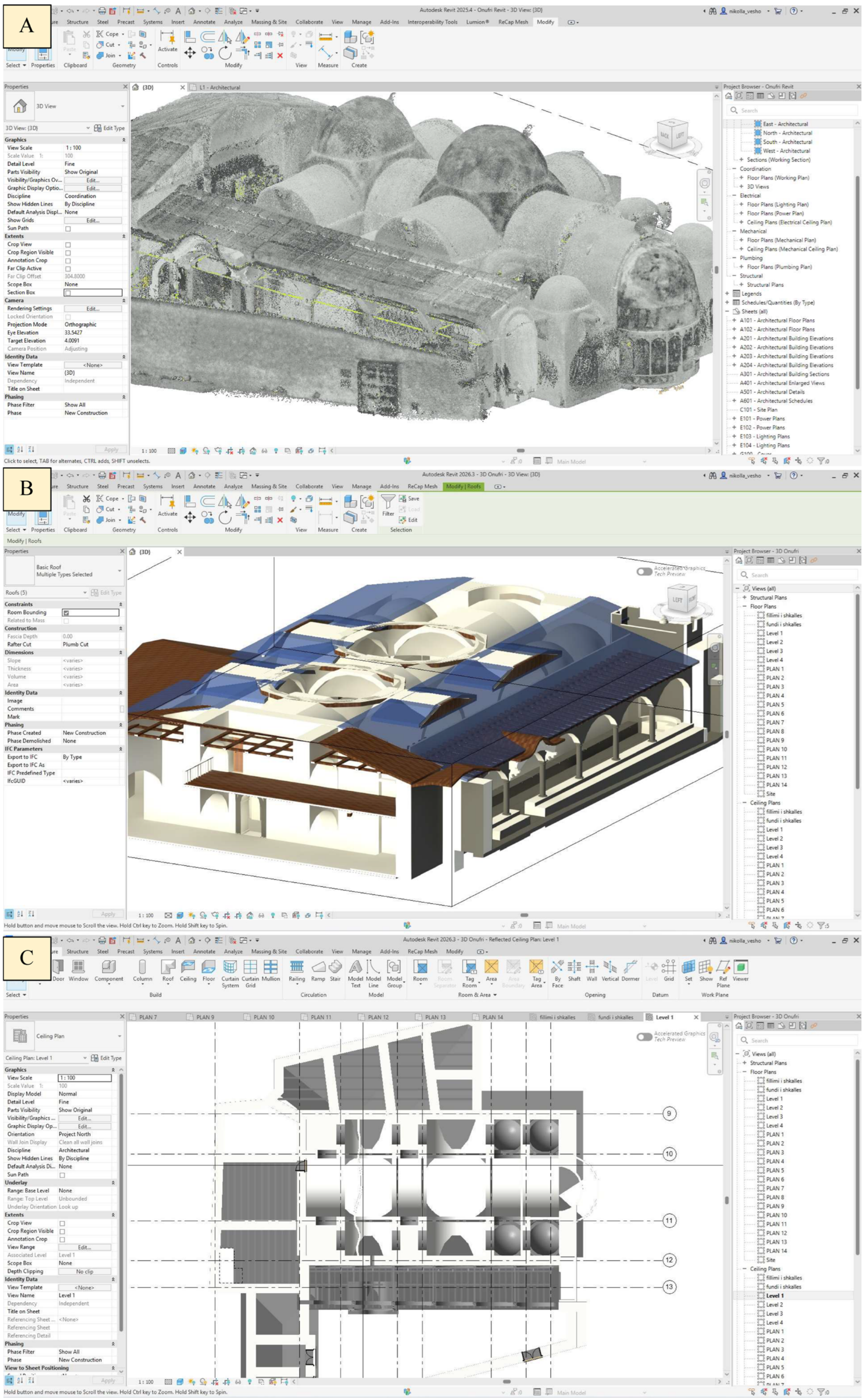

Figure 8. Transition from FJD point cloud to building information modeling (BIM) environment. (A) Complete point-cloud model of the church fully integrated into Autodesk Revit. (B) Isometric analysis within the BIM environment using the Section Box tool, highlighting the principal architectural and structural forms. (C) Plan-level morphological analysis generated through the Section Box tool, illustrating spatial organization.

Figure 9. Interior visualizations of the church and the iconographic museum generated from the base building information model. Renderings were refined through the Autodesk Revit-TwinMotion plugin integration to achieve photorealistic accuracy and enhanced spatial representation.

6.1. Methodological contribution

The proposed workflow merges heterogeneous survey data into a unified HBIM framework, preserving geometric deviations for analysis rather than smoothing them away. This approach contrasts with common scan-to-BIM practices that prioritize parametric abstraction over measurable accuracy. By aligning dense point-cloud sections with parametric modeling, the study elevates HBIM from representational output to a diagnostic instrument for structural inquiry.[1,5,6,8]

6.2. Reliability and limitations

Cross-validation between photogrammetric and LiDAR datasets ensured metric consistency within conservation-grade tolerances.[7,12] Explicit modeling criteria prevented loss of fidelity in irregular elements. Acknowledged limitations include incomplete semantic detail and material encoding, which remain avenues for future integration.[2,4]

6.3. Implications for heritage contexts

The workflow demonstrated concrete analytical advantages in a complex ecclesiastical context, capturing non-orthogonal geometries and structural asymmetries that are critical for seismic heritage assessment. Such capabilities improve understanding of deformation patterns without intrusive interventions.[13,14]

6.4. Transferability and future directions

The methodology is adaptable to other heritage sites with restricted access and irregular form. Future work should aim to enhance semantic representation by incorporating archival data, material characterization, and sensor-based monitoring to support predictive conservation models.[2,5,6]

7. Conclusions

This study has demonstrated the effectiveness of an integrated digital documentation workflow that combines UAV-based photogrammetry, mobile LiDAR scanning, and HBIM modeling for comprehensive analysis of complex ecclesiastical heritage. Applied to the Onufri National Museum in Berat, the proposed methodology enabled the generation of a geometrically reliable, analytically transparent, and conservation-oriented digital representation that exceeds the descriptive capacity of conventional survey techniques. By prioritizing geometric verification and data traceability throughout the point-cloud–to–HBIM transition, the research addresses a critical gap in current HBIM practice, in which interpretative abstraction often compromises metric fidelity. The identification of non-orthogonal geometries, dome asymmetries, and structural hierarchies not documented in archival sources confirms the added diagnostic value of hybrid survey integration in heritage contexts characterized by irregular morphologies and incremental construction phases.

Beyond site-specific outcomes, the study contributes a transferable methodological framework adaptable to similar heritage assets located in dense urban environments and seismically active regions. The reliance on interoperable, commercially available technologies enhances the practical applicability of the workflow for heritage professionals, institutions, and academic settings operating under constrained resources. The research further clarifies the role of HBIM not merely as a representational medium, but as an analytical and decision-support instrument capable of linking geometry, structure, and observed pathologies within a unified digital environment. This positioning aligns HBIM practice more closely with conservation-oriented objectives, supporting informed assessment, documentation, and long-term management strategies.

Finally, the study acknowledges current limitations in semantic depth, material characterization, and the integration of performance-based data. Future research should focus on extending the HBIM framework by incorporating archival records, NDT data, and sensor-based monitoring, thereby advancing toward a more comprehensive and dynamic digital twin paradigm for historic structures.

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Conflict of interest

The authors declare they have no competing interests.

Author contributions

Conceptualization: All authors
Data curation: All authors
Formal analysis: All authors
Investigation: All authors
Methodology: All authors
Resources: Nikolla Vesho, Panagiotis Kyratsis
Visualization: Nikolla Vesho, Klodjan Xhexhi, Romir Mazari
Writing–original draft: All authors
Writing–review & editing: Nikolla Vesho, Panagiotis Kyratsis

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

Data are available upon request from the corresponding author.

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