Combining HBIM and AR for Heritage Conservation. From Digital Survey to an Interactive Management Tool

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Abstract

This paper presents a Scan-to-HBIM-to-XR workflow aimed at supporting preventive and planned conservation of complex architectural heritage. The proposed methodology integrates multi-source 3D surveying, semantic information modelling, and Augmented Reality (AR) technologies into a unified operational framework. Terrestrial Laser Scanning (TLS) and UAV-based photogrammetry are combined to generate an accurate and georeferenced digital replica, which forms the basis for the development of a semantically enriched HBIM model. The model is structured to integrate geometric, historical, construction, and diagnostic data, including quantitative indicators for assessing masonry quality and conservation status.

To enhance accessibility and usability, the HBIM dataset is connected to a lightweight AR application that enables on-site consultation and updating of alphanumeric BIM data. Through spatial alignment with the real architecture, users can document degradation phenomena, create AR-based segmentations and georeferenced annotations, and transmit updates to a cloud system, where they are automatically integrated into the HBIM model, ensuring a continuous feedback loop between field activities and the central model. Tested on the historic city walls of Fano (Italy), the workflow demonstrates how HBIM and AR can be combined to transform digital models into dynamic decision-support tools, bridging the gap between documentation, monitoring, and long-term heritage management.

1. Introduction

In recent years, the integration of accurate 3D surveying techniques, information modelling, and eXtended Reality (XR) technologies has become a well-established strategy in the field of Architectural Heritage (AH) documentation and conservation. This convergence reflects a broader shift in digital heritage practices, where the generation of geometrically accurate 3D models is increasingly coupled with the need to structure, interpret, and manage heterogeneous information over time. Within this framework, digital representation is no longer conceived as a purely descriptive output, but as a foundational component of knowledge-based systems aimed at supporting conservation-oriented decision-making processes (Dimitrova et al. 2020; Bucharest Manifesto 2024).

The modelling of knowledge for the conservation and management of AH is generally structured around two complementary processes: the digital representation of architectural geometry and the hierarchical organization of information. Together, these processes enable the creation of digital environments capable of georeferencing, semantically structuring, and interrelating data from different sources, supporting preventive and planned conservation strategies. In this context, reality-based survey techniques play a central role, as they provide the metric foundation for any subsequent analytical or interpretative activity. Laser scanning and photogrammetry, in particular, have enabled the production of highly accurate 3D datasets, typically starting from point clouds that can be further processed into mesh models or used as a reference for parametric modelling (Brusaporci, 2015). Each representation addresses different needs: point clouds ensure morphometric accuracy, mesh models offer detailed surface characterization, while parametric models support data integration and advanced management workflows.

Within this evolving panorama, Heritage Building Information Modelling (HBIM) has emerged as one of the most effective methodologies for the medium- and long-term conservation and management of AH (Di Stefano et al., 2020; Jouan and Hallot, 2019). Since its early formalization (Murphy et al., 2009), HBIM has generated an extensive body of scientific literature, highlighting both its potential and its critical limitations (López et al., 2018; Penjor et al., 2024). One of the main challenges lies in the fact that HBIM environments are commonly implemented using BIM software originally conceived for new constructions. This condition raises significant issues related to the faithful digital reconstruction of irregular, diachronic geometries and to the management of heterogeneous information according to semantics coherent with conservation practices (Murphy et al., 2013; López et al., 2018; Simeone et al., 2019; Acierno and Fiorani, 2025).

In typical HBIM workflows, architectural modelling is largely based on TLS and photogrammetric data (Diara et al., 2019; Alshawabkeh et al., 2021; Ferretti et al., 2022). However, scan-to-BIM processes remain predominantly manual and time-consuming (Quattrini et al., 2015; Allegra et al., 2020), particularly when dealing with complex masonry systems. Recent research has therefore focused on the development of innovative approaches aimed at improving modelling efficiency and flexibility, including the use of reality-based mesh models (Angeloni et al., 2023) and the integration of AI techniques for feature recognition and semantic support (Andriasyan et al., 2020; Abreu et al., 2023; Croce et al., 2023). An important research direction is represented by hybrid environments in which point clouds, meshes, and BIM objects coexist and are used simultaneously (Brookes, 2017). These approaches enable the integration of data derived not only from TLS and photogrammetric surveys (Spettu et al., 2021), but also from non-destructive diagnostic techniques (Garcia-Gago et al., 2022; Mugnai et al., 2023), supporting a more informed interpretation of conservation issues. Despite their potential, hybrid workflows are still only partially supported by mainstream BIM platforms, highlighting the need for complementary tools and interoperable systems.

To address these limitations, recent studies have increasingly focused on the development of shared platforms and dedicated management tools. The European HeritageCare project, for instance, demonstrates how raw point clouds can be enriched with structured data and immersive visualization, transforming HBIM environments into effective knowledge infrastructures for conservation planning and comparative analysis over time (Mora et al., 2021; Masciotta et al., 2021; Masciotta et al., 2023). Similarly, Clini et al. (2024) propose the integration of multiple 2D and 3D representations within HBIM environments to support preventive conservation and maintenance strategies, enhancing data accessibility and interdisciplinary collaboration.

In parallel, several studies have explored the integration of HBIM with other digital environments, particularly GIS platforms (Vacca et al., 2018; Matrone et al., 2023; Fortunato et al., 2025), as well as the development of point-cloud-based platforms in emergency contexts, such as the digital reconstruction of Notre-Dame Cathedral (Roussel and De Luca, 2023; Néroulidis et al., 2024). These experiences underline the importance of interoperability and long-term data management in complex heritage scenarios.

More recently, the integration of HBIM with XR technologies has opened new perspectives by extending digital models beyond desktop-based environments. Scan-to-HBIM-to-XR pipelines have demonstrated their effectiveness in linking semantically structured models with on-site inspection and analysis activities (Banfi et al., 2022). XR tools are increasingly conceived not merely as visualization layers, but as interactive interfaces enabling users to query, annotate, and update model-linked data directly in situ, supporting long-term conservation through the prioritization and scheduling of tasks (Assefa et al., 2025; Clini et al., 2025).

Building upon this state of the art, this paper proposes a Scan-to-HBIM-to-XR workflow (Figure 1) specifically designed for historic masonry systems and tested on the city walls of Fano (Italy). The proposed methodology integrates multi-scale 3D survey data acquired through TLS and UAV photogrammetry with a semantically enriched HBIM model oriented toward conservation analysis and management. The workflow is further extended through an AR-based interactive tool that enables on-site expert interaction with the digital model, supporting a preventive, knowledge-driven, and sustainable approach to the conservation and management of AH.

2. Methodology and case study application

The methodological framework adopted in this research is conceived as an integrated and scalable workflow aimed at supporting the documentation, on-site inspection, conservation and management of complex AH systems. The city walls of Fano, distinguished by their centuries-old history, extension, stratification, and heterogeneous conservation conditions, represent an exemplary case for testing a methodology that combines high-resolution 3D survey techniques, semantic information modeling, and virtual interaction tools within a unified digital environment.

The workflow is structured around the concept of a digital replica that evolves from a geometrically accurate representation into a semantically enriched information system, capable of supporting preventive and planned conservation strategies. Rather than treating survey, modeling, and visualization as independent phases, the methodology establishes a continuous and bidirectional relationship between data acquisition, analytical interpretation, and operational use. In this perspective, the digital model is not conceived as a static archive, but as a dynamic system designed to be updated, queried, and validated over time.

The methodological process is articulated into three main phases:

- *Data acquisition* (2.1): the first phase focuses on the acquisition of geometric data through the integration of Terrestrial Laser Scanning (TLS) and UAV-based photogrammetry, ensuring metric accuracy and completeness in the representation of the architectural system.
- *Data processing* (2.2): the second phase concerns survey data processing to obtain a 3D model, enriched with semantic information related to construction techniques, stratigraphic relationships, material characteristics, and conservation conditions. Within this phase, the Masonry Quality Index (IQM) is implemented as a quantitative parameter to support diagnostic assessment and comparative analysis.
- *Implementation* (2.3): The third phase introduces an XR-based tool designed as an operational interface for in situ interaction with the enriched model, enabling data consultation, annotation, and updating directly in the field.

This methodological framework aims to bridge the gap between digital documentation and conservation practice, providing a coherent and interoperable system capable of supporting both analytical interpretation and decision-making processes related to the management of AH.

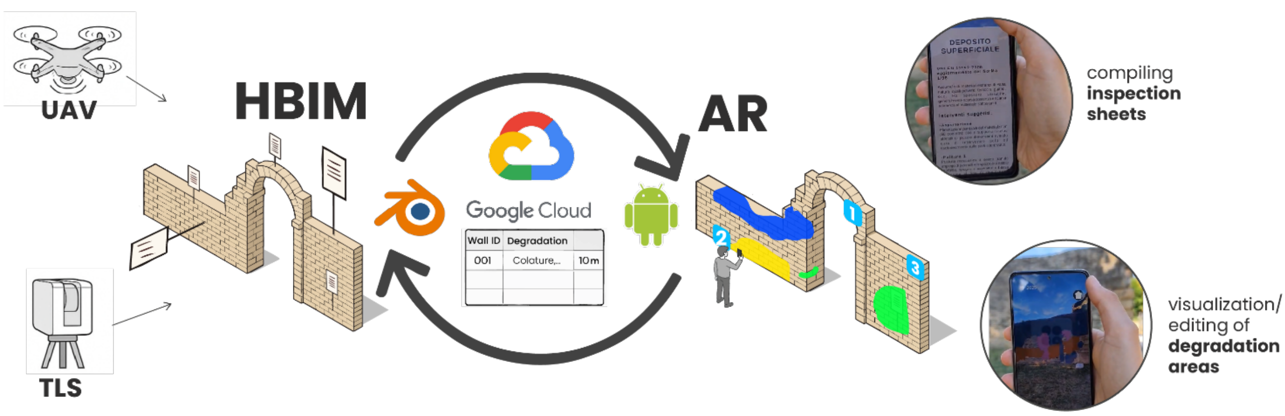

Figure 1. Workflow of the proposed methodology.

Figure 2. Detail of the masonry texture reconstructed in 3D through laser scanning.

2.1 Data acquisition

The data acquisition phase represents the foundational step of the proposed methodology, as it provides the geometric and metric basis upon which all subsequent modeling, analysis, and interaction processes are built. Given the complexity and extension of the city walls of Fano, an integrated multi-scale survey strategy was adopted to capture both the overall configuration of the defensive system and the local details required for conservation-oriented analysis.

TLS was employed as the primary technique for documenting vertical and sub-vertical surfaces, including wall elevations, towers, gates, and areas characterized by material decay and structural discontinuities. The TLS survey was carried out using a Leica ScanStation P40 and Leica RTC360. Scan positions were carefully planned along the perimeter of the walls to ensure uniform coverage, reduce shadow zones, and capture both external and internal faces of the masonry where accessible. The 119 individual scans acquired were registered using a cloud-to-cloud alignment procedure, allowing the generation of a unified and metrically consistent point cloud. This approach ensured high geometric reliability without the need for an extensive target-based network, while maintaining sufficient accuracy for detailed modeling and diagnostic purposes. The resulting TLS dataset provided a representation of surface geometry, enabling the identification of construction techniques, material textures, degradation and deformation patterns relevant to conservation assessment (Figure 2).

To complement the terrestrial survey and overcome limitations related to accessibility and line-of-sight constraints, a UAV-based photogrammetric survey was conducted using a DJI Mavic 3T. The aerial acquisition focused on the upper portions of the walls, tower crowns, and horizontal surfaces that are typically difficult to document from ground level. Over 4200 high-resolution images were acquired following a flight plan designed to ensure sufficient overlap and image quality for photogrammetric processing. The images were processed using a Structure-from-Motion (SfM) workflow combined with dense image matching techniques, resulting in a photogrammetric point cloud capturing roof-level and upper masonry features.

The TLS and UAV-derived datasets were subsequently integrated within a common spatial reference system using GNSS-RTK–acquired GCPs, ensuring metric coherence and interoperability between the different sources. The combined dataset offers a comprehensive and multi-scale geometric representation of the city walls, balancing global completeness with local detail. This unified point cloud constitutes the geometric foundation for the subsequent 3D modeling and data enrichment phase, enabling a consistent transition from survey data to semantic interpretation and conservation-oriented analysis (Figure 3).

2.2 3D modeling and data enrichment

The integrated TLS and UAV point cloud constituted the geometric basis for the construction of a three-dimensional information model oriented toward conservation analysis and management. In accordance with the methodological framework outlined in Section 2, the modeling phase was conceived not merely as a process of geometric reconstruction, but as a semantic interpretation of the architectural system, aimed at structuring heterogeneous data within a coherent and queryable environment.

The modeling activities focused on the pilot area of Porta della Mandria and the adjacent towers and curtain walls. A component-based approach was adopted, allowing the subdivision of the walls into homogeneous portions according to construction techniques, material characteristics, stratigraphic relationships, and visible traces of transformation. This segmentation was informed by direct observation of the masonry fabric, archival documentation, and previous diagnostic investigations, enabling the distinction between original Roman structures, medieval and early modern modifications, and integration works related to restoration campaigns carried out during the twentieth and early twenty-first centuries.

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Figure 3. View of a portion of the point cloud of the Walls of Fano, derived from the integration of TLS and UAV photogrammetry.

Each modeled element was associated with a structured set of attributes designed to support conservation-oriented analysis. These attributes include construction phase, masonry typology, material composition, stratigraphic layers, and references to historical sources and restoration records – the latter derive mainly from archival research. Areas affected by decay and alteration phenomena were spatially identified and described using standardized terminology derived from conservation guidelines and technical standards. This approach allowed the model to function as a centralized repository of both geometric and descriptive information, facilitating a comprehensive understanding of the architectural system and its state of conservation.

A key aspect of the data enrichment process was the integration of the Masonry Quality Index (IQM – Indice di Qualità Muraria) as a quantitative parameter supporting diagnostic assessment (Borri and De Maria, 2019). The IQM was calculated for each homogeneous wall portion by evaluating a set of parameters related to construction rules, material characteristics, and mortar quality, considering vertical actions, in-plane actions, and out-of-plane actions. The resulting values provide a synthetic representation of the constructive quality and structural reliability of the historical masonry, enabling comparative analysis across different wall sections.

The IQM values were directly linked to the corresponding modeled elements as structured attributes within the information model. This integration enables thematic visualization of construction quality and conservation conditions, supporting the identification of critical areas and the prioritization of intervention strategies. By embedding quantitative indicators within the same environment used for geometric representation and qualitative description, the model facilitates a direct connection between survey data, analytical evaluation, and conservation planning. Through this modeling and data enrichment strategy, the 3D model becomes an operative information system supporting diagnostic interpretation, monitoring, and conservation actions. The entire workflow was implemented in the open-source Blender environment using the Bonsai add-on, resulting in an HBIM model serving as the primary reference for the structured organization and long-term management of geometric and semantic information. (Figure 4).

2.3 XR tool

The third phase of the methodology concerns the development of an Augmented Reality (AR) application conceived as an operational interface for the on-site access, consultation, and updating of the information contained in the HBIM model (Figure 5). The AR tool is integrated within an interoperable workflow that connects the modeling environment, a cloud-based infrastructure, and a mobile application running on Android devices, with the aim of ensuring continuity between modeling activities, on-site inspection, and data management. However, the HBIM model is not transferred directly to the AR application. Instead, the data required for on-site visualization and interaction are organized and made available through a cloud-based infrastructure built on Google Cloud, which acts as the central node for data storage, synchronization, and sharing. Within this infrastructure, Google Drive is used for the storage of digital assets, including derived models, simplified geometries, images, and technical documentation, while Google Sheets is employed as a flexible data structure for managing alphanumeric information associated with architectural elements and degradation entities. This solution allows heterogeneous data to be managed within a unified system, while maintaining a structure that can be easily queried and updated from different environments. Access to cloud services is mediated by a Web App, which functions as an interface layer between the BIM environment, the AR application, and the cloud infrastructure. The Web App centralizes data read and write operations, avoiding direct access to cloud service APIs from client devices. In this configuration, the AR application functions as a lightweight client that queries the system and submits updates through standardized requests, keeping the BIM environment and cloud infrastructure decoupled from the mobile application.

From the AR functionality perspective, the system is based on an environment-based tracking approach using an Area Target. The Area Target was generated from the three-dimensional point cloud of the city walls of Fano, derived from the TLS survey campaign described in the data acquisition phase. The point cloud was processed to produce a spatial reference that provides a concise yet accurate description of the real environment, enabling automatic recognition of the architectural context by the AR application. The use of an Area Target derived from reality-based data overcomes the limitations of marker-based tracking systems

Figure 4. View of the 3D model with degradation mapping, where erosion areas are identified and segmented as *IfcBuildingElementProxy* within the HBIM model to support analysis, monitoring, and planned conservation activities.

Figure 5. Main AR functionalities of the smartphone application: a) visualization of past restorations directly on the architecture; b) color-coded mapping of conservation state and degradations; c) access to Masonry Quality Index (IQM) results and related interpretative information; d) management of on-site inspections, including consultation of previous records and creation of new ones.

and is particularly suitable for extended and complex architectural environments. When the user frames the walls with a smartphone, the application compares the data acquired from the device's camera and sensors with the spatial reference defined by the Area Target, determining the position and orientation of the device relative to the real architecture. Once spatial alignment is established, digital content is displayed overlay on the corresponding wall surfaces. This mechanism enables stable and repeatable visualization of digital information, even in outdoor environments characterized by variable lighting conditions and complex geometries. The adoption of the Area Target also ensures compatibility with established AR frameworks such as Vuforia, allowing the application to run on standard mobile devices without the need for specialized hardware configurations.

3. Results

The following section presents the results of the proposed workflow, illustrating how the AR tool enables access, visualization, and on-site acquisition of semantic information. Through a mobile device, users can access contextual data associated with the architectural elements being observed. Selecting a wall portion or a specific architectural component triggers a request to the cloud-based system, which returns the associated data in the form of textual information, numerical values, or references to documentation stored in the cloud. In this way, the AR application does not locally store the information dataset, but functions as an interface for dynamic access to a distributed information system. A relevant operational function concerns the documentation of degradation phenomena observed during on-site inspections. By exploiting the spatial alignment provided by the Area Target, users can identify and record degradation areas directly on the real architecture (Figure 6). The collected information includes spatial localization, descriptive attributes, and photographic documentation acquired on site. These data are transmitted to the cloud infrastructure and made available for subsequent integration into the HBIM model. Degradation is managed as an information entity associated with architectural elements, keeping the primary wall geometry separate from interpretative and conservation-related data.

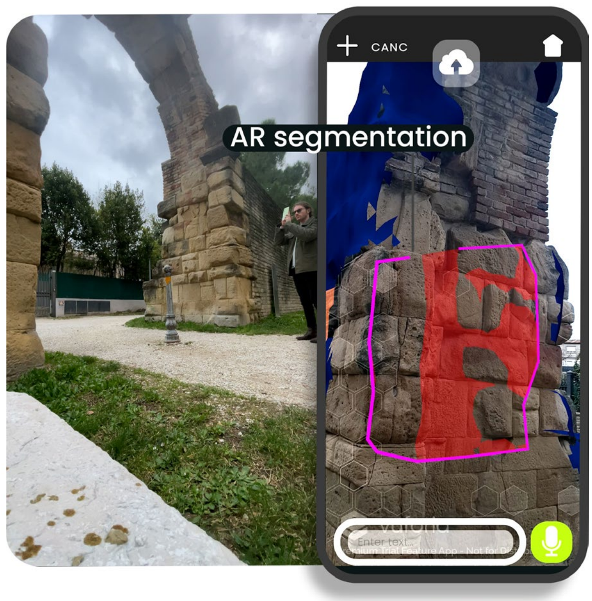

Figure 6. Users can define decay areas directly on the masonry through touch-based vertex placement, visualize the interpolated surface in real time, and record decay typology via voice input. The resulting data are exported as JSON and synchronized with the HBIM environment.

Figure 7. The operator frames a specific portion of the masonry using a mobile AR interface; a tap generates a georeferenced annotation anchored to the real structure. The annotation can be recorded via voice input or text and is then transmitted to the cloud, where it is automatically converted into a JSON file readable and interoperable with the HBIM environment.

This approach allows complex and discontinuous phenomena to be documented without altering the architectural representation, preserving the consistency of the HBIM model, and supporting diachronic analysis.
The system supports the management of multiple degradation phenomena associated with the same architectural element, enabling the representation of heterogeneous conservation conditions and the recording of successive updates over time.

Within the same AR environment, users can also create georeferenced AR annotations, which are seamlessly integrated into the HBIM model as contextual on-site observations (Figure 7). The use of flexible cloud-based data structures allows degradation data and annotations to be queried and updated efficiently, supporting monitoring activities and conservation planning. The AR application further enables the consultation and editing of alphanumeric information associated with architectural elements and degradation entities. Modifications performed on site are transmitted in real time to the cloud system and subsequently made available for updating the information model.

4. Conclusion

The proposed workflow demonstrates how HBIM models of complex and extensive architectural heritage can function as operational and decision-support tools for sustainable conservation management. By integrating multi-source 3D documentation, HBIM-based semantic structuring, and AR-based visualization and on-site editing, the study defines a scalable and replicable methodology that effectively bridges digital representation and field-based heritage practice (Figure 8).
The workflow combines geometric accuracy, semantic modelling, and interactive tools, transforming the HBIM model into a dynamic system for diagnosis, monitoring, and conservation planning. Multi-scale survey data ensure a reliable representation of complex masonry systems, while structured semantic information supports the management of historical, material, and diagnostic data. The introduction of the Masonry Quality Index (IQM) as a parametric attribute enables quantitative assessment of structural conditions which, together with the AR-based segmentation and mapping of degradation phenomena, supports comparative analysis and the prioritization of conservation interventions.

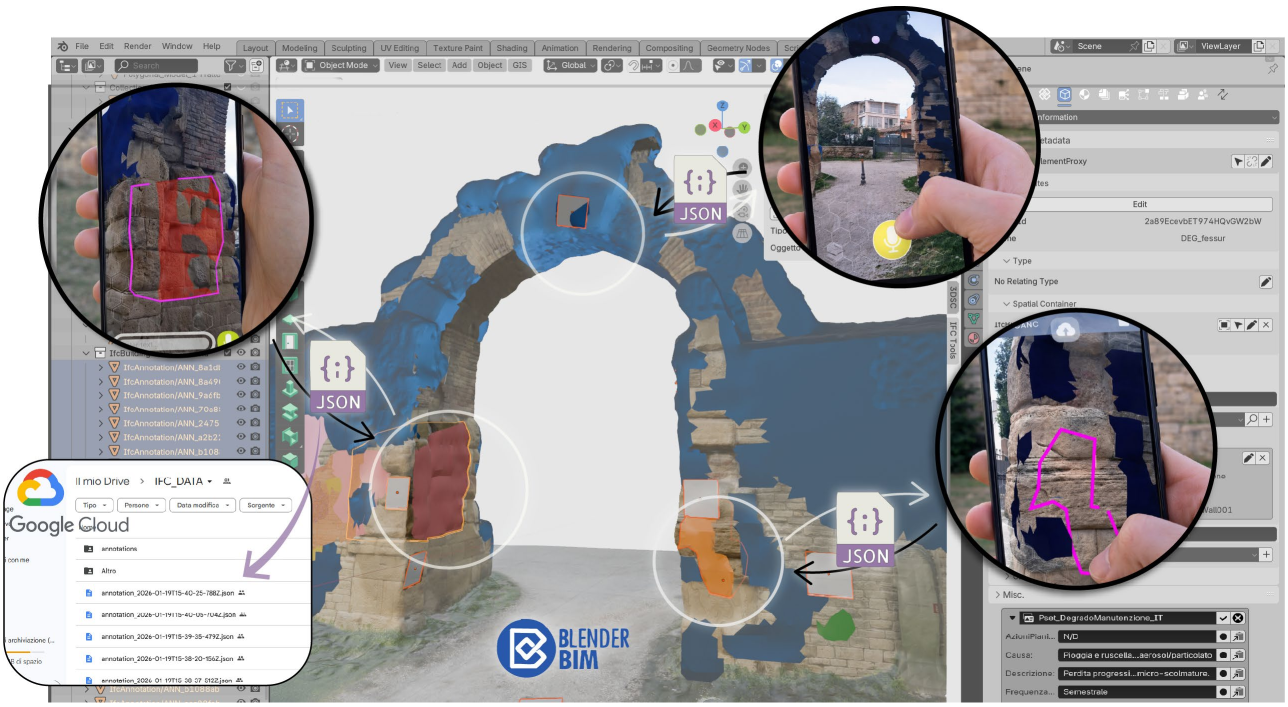

Figure 8. The figure shows the on-site AR preview of the operations and the corresponding final result in the HBIM model. Georeferenced annotations are represented as grey *IfcAnnotation* elements, while decay segmentations are imported as colored *IfcBuildingElementProxy* elements, with colors reflecting the associated decay typology and linked to the parent *IfcWall*.

The use of AR as an on-site interface extends the HBIM model beyond a static repository, enabling direct interaction with the digital replica in situ. Experts can consult and edit alphanumeric BIM data, generate georeferenced annotations, and define or update degradation segmentations directly on the architecture. Data recorded on site are transmitted to a cloud-based system and automatically integrated into the reference HBIM model, establishing a continuous feedback loop between field operations and the central information environment. This approach reinforces HBIM as a dynamic framework for adaptive and knowledge-driven heritage conservation.

From a broader perspective, the methodology contributes to redefining the concept of conservation, from 'reactive' restoration to 'proactive', knowledge-driven management (Della Torre 2021). The proposed framework has the capacity to be adapted for use in other historic sites, with particular relevance to historic urban systems. The case of city walls exemplifies heritage sites that persist in contemporary society and the environment without a specific use, yet whose presence is essential for understanding the processes of urban development in which they continue to play a fundamental role. For such heritage, ensuring sustainable preservation requires support from advanced digital tools that optimize both conservation and management processes.

Future developments will focus on integrating automated data analysis, such as AI-assisted recognition of decay typologies from high-resolution imagery, and on the use of IoT-based sensor networks for the acquisition of real-time environmental and structural data. In this sense, this workflow aligns with ongoing research trends that aim to transform HBIM models into fully operational digital twins for heritage conservation and management, supporting both heritage professionals and institutional decision-makers in the sustainable care of our built environments.

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