BIM-AR Interactive Data Accessibility in Cultural Heritage: a VPL Integrated Approach

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Abstract

The integration of digital technologies aimed at the knowledge of the existing built heritage is now a well-established practice in the scientific field. The objective remains the optimization of methodologies intended to coordinate different needs, ranging from the integration of technical and documentary aspects to the enhancement of communication and dissemination of knowledge of heritage assets. While Heritage Building Information Modelling (HBIM) represents the most widespread methodology for Facility Management (FM), enabling control over the entire life cycle of buildings, the challenge lies in integrating Extended Reality (XR) tools, which allow operators to consult, update, and interact immersively with digital models, expanding their potential both for technical management and for heritage valorization. In this direction, the contribution proposes a workflow that integrates Augmented Reality (AR) into Heritage Building Information Modelling (HBIM) processes, enabling real-time updating of information through on-site observations. The case study concerns the complex of Santa Maria del Rifugio in Naples (Italy), characterized by historical stratifications from the 15th to the 20th century and by complex structural and conservation conditions. Starting from the digital survey, the information model was enriched with dimensional and analytical metadata, synchronized in AR through the structuring of a Visual Programming Language (VPL) algorithm that promotes the overlap between real and virtual through Image Targets, interaction with data stored in the BIM Common Data Environment (CDE), and their real-time updating. The result is an interactive system that enhances understanding, management, and valorization of cultural heritage, offering an engaging cognitive and immersive representation of architecture.

1. Introduction

In recent years, scientific research has shown a growing interest in the integration of digital solutions applied to the existing built heritage, with the aim of developing efficient workflows capable of addressing, in an integrated manner, the needs of documentation, technical management, use, and dissemination of heritage assets. A key tool for structuring Facility Management processes is undoubtedly Heritage Building Information Modelling (HBIM), as it enables the control and management of the entire life cycle of buildings (Durdyev et al., 2022; Lovell et al., 2024); The challenge that remains open lies in the possibility of integrating interactive Extended Reality (XR) tools, enabling models to support advanced digital use that allows operators not only to consult and update information models, but also to interact with them in an immersive manner closely connected to the physical built environment, thereby expanding their potential both for technical management and for the dissemination and valorization of heritage assets (Argiolas et al., 2022). In this context, the contribution positions itself within the broad and ongoing discussion on digital interoperability between HBIM and XR systems for the management and valorization of cultural heritage (Sidani et al., 2021; Teruggi and Fassi, 2022; Antuono et al., 2024, Vindrola et al., 2024), and proposes a workflow for the reading and manipulation of parametric–informational data in Augmented Reality (AR), enabling real-time feedback directly on the digital model under conditions of coordinated real–virtual overlay. By focusing on the complex forms of historic heritage, the workflow was developed to overcome the limitations in translating CSG (Constructive Solid Geometry) geometries, typical of BIM-based shape construction, into B-Rep (Boundary Representation), to facilitate their visualization in AR. This is achieved through the development of specific algorithms, which find in VPL (Visual Programming Language) the most flexible tool (Lanzara et al., 2024) to overcome interoperability limitations between platforms, while at the same time offering the possibility of semi-automatically managing the AR visualization, aligned with reality, of information related to complex elements. The workflow was tested on a religious complex, characterized by an enclosed church within a building that formerly housed a nunnery, nowadays a school. This investigation aims not only to enable a more precise and informed management of information, but also to establish an advanced platform for the enjoyment and dissemination of the built environment, opening the way to an immersive and participatory reading of the building, supported by a methodological path ranging from data collection, interpretation, and digitization to the construction of the HBIM-AR model.

1.1 Methodological notes

The adopted methodology (Figure 1) is based on an integrated approach that supports the entire process, from the knowledge and documentation phase of the heritage asset to its fruition through Augmented Reality (AR). The workflow begins with digital surveying and the analysis of cartographic and iconographic sources, which, through a phase of data analysis and integration, led to the construction of a parametric-informational model of the complex, organized by historical phases and enriched with dimensional and analytical metadata. This information, which includes the characteristics of elements (e.g., period and dating) as well as data regarding conservation status and deterioration, can be accessed directly through the AR application via a dedicated VPL algorithm, ensuring that interactive data and multimedia content stored in the BIM Common Data Environment (CDE) overlay the physical reality to generate a functional and immersive cognitive representation of the architecture.

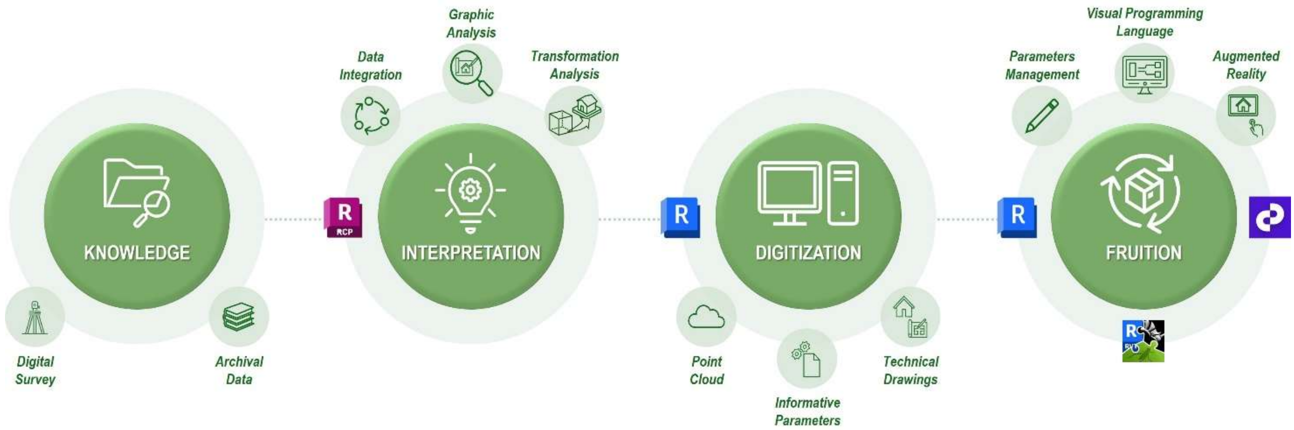

Figure 1. Methodological diagram of the research: from the phase of knowledge acquisition, interpretation, and data digitization to their fruition in Augmented Reality.

This phase represented the core of the research, in which the algorithm was structured into three parts: filtering and synchronization of geometries, identification and reconnection to informational IDs, and management of parameters either newly created or retrieved from the model. In parallel, an Image Target system ensures the alignment between real and virtual coordinates, as well as the correct scaling of digital content. To enable the development of the workflow, the BIM platform was enhanced with the necessary tools through the Rhino.Inside.Revit plugin, which allows the use of Grasshopper functionalities - a visual programming environment integrated into the modeling tools - also required for the operation of the Fologram Augmented Reality platform. This approach was tested on the interior spaces of the Santa Maria del Rifugio complex in Naples, , in the southern Italy, an example of architecture characterized by complex historical stratification and a severely compromised state of conservation. The case study proved to be emblematic due to the need for maintenance and restoration interventions, as well as the requirement for extensive dissemination of its historical and architectural values. It allowed for experimentation with direct interaction between operators and the digital model, updated in real time, supporting technicians in recording and verifying conditions directly on site.

2. The S.M.del Rifugio Complex: from Survey to Model

The study of a highly stratified architectural heritage is particularly complex, especially when it is situated within a context that has been in continuous and incessant transformation for millennia, with ancient *Neapolis* providing a tangible example (Longo, 2017) (Figure 2). In this context, the Santa Maria del Rifugio complex also has ancient origins (Ferraro, 2002), and the presence of profound transformations is evident: level changes between exterior and interior, altimetric variations within the same floors, heterogeneous access and connection systems, load-bearing structures of different types, irregular arrangement of openings, and diverse functional uses all highlight the delicacy of any approach to the building (Antuono et al., 2025). For this reason, structured documentation is essential, encompassing accurate surveying of the asset, its digitalization, and the reconstruction of a digital model that allows a diachronic and informative reading of all components of the complex.

2.1 Integrated Digital Survey

The systematic digitalization of the entire complex was necessary not only to update the existing drawings, but above all to reveal information that would otherwise be difficult to deduce, as well as to gain a better understanding of the spatial and geometric relationships between its components (D'Auria, 2024).

Putting aside the purely procedural and technological aspects related to the surveying and subsequent data processing phases (De Marco and Parrinello, 2022), terrestrial photogrammetry (using common smartphones and DSLR cameras) was mainly employed for surveying specific areas of the complex, such as the Church of Santa Maria del Rifugio, with the aim of producing outputs for documenting the current state and decorated surfaces. Aerial photogrammetry (conducted through five Visual Line Of Sight, VLOS, flights) provided data for modeling some façades, the complex's roofs, and, above all, the urban layout of the insula. Laser scanning (with over 300 internal and external scans) enabled the systematic digitalization of the entire complex, including portions of Via dei Tribunali, Vico Rifugio ai Tribunali, and Vicoletto di Santa Maria ad Agnone, which delimit the study area. During the digitalization phase, particular attention was paid to the stairwells and the long, narrow corridors: even minimal alignment errors could have caused noticeable rotations of parts of the model, which, given the building's large scale, could have compromised its critical reading as well as subsequent parametric modeling operations. The documentation activities also made use of a 360° camera to create virtual tours for enhancing the physical and cultural accessibility of the site. Furthermore, the various point clouds produced from the survey campaigns were integrated into a single model (Figure 3), which allowed for precise analysis of the building's geo-morphological aspects and provided a reliable data foundation for the subsequent structuring of a semantic HBIM model (Raco et al., 2022) through scan-to-BIM operations.

Figure 2. Territorial framework of the complex.

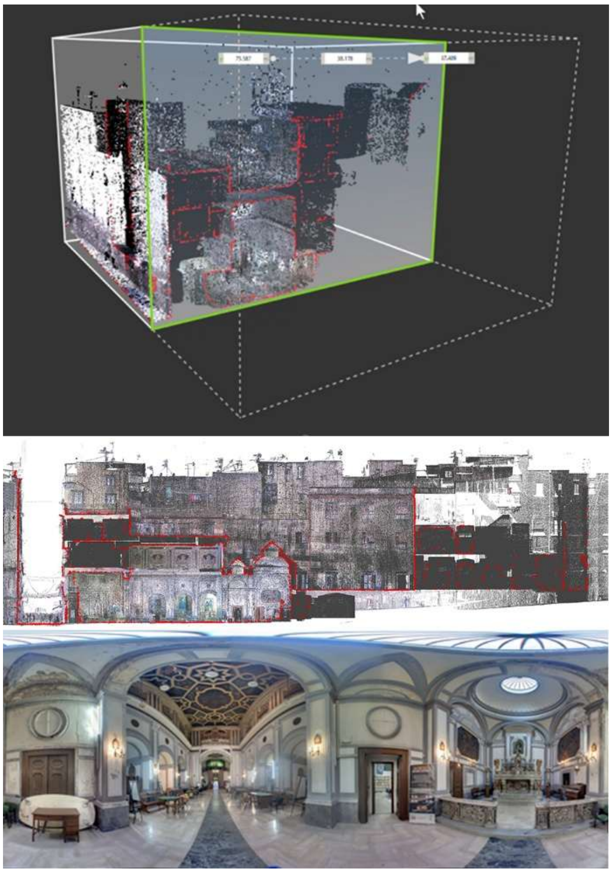

Figure 3. Examples of digital survey outputs. From top: portion of the point cloud with a section box; a longitudinal section of the model; a panoramic photo of the church.

2.2 From Survey to the Parametric-Informational Model for AR

The process of data populating led to the development of a parametric model based on the point cloud, using established scan-to-BIM procedures (Badenko et al., 2019; Intignano et al., 2021). The persistent discrepancy between the rigidity of object-oriented modeling structures and the high variability typical of built heritage elements made it necessary to create new libraries of parametric objects, as well as to define the most appropriate methods for digitizing construction elements (Delpozzo et al., 2022) and degradation paths (D'Agostino et al., 2023), in order to develop a semantically aware 3D model. This process enabled the digitalization of the components of the overall spatial system, integrating specific informational and documentary attributes into the model, for example relating to technological systems (Achille, et al., 2020; Navarro, 2023), and systematizing data from historical and archival documentation, including records of previous interventions, thereby ensuring the digital reconstruction of different phases and a diachronic reading of the asset (Figure 4).
For the digitization of architectural elements, a preliminary action was necessary to identify the components of the overall spatial system, with particular attention to the structures encompassing the church space (Figure 5). This operation was based on a process of decomposition and recomposition of the 'spatial box,' through a multi-level semantic decomposition: from a general, spatial and environmental level to progressively more detailed levels. Each semantic entity, corresponding to the different levels of analysis, was assigned a unique identification code, enabling the construction of a true semantic tree, composed of coded entities and specifically associated informational descriptions (Cera, 2019). The first level of semantic recognition involved identifying the functional spaces that make up the complex (such as the church (CH), courtyards (CRT), sacristy (SCR), etc.). This was followed by a classification level for the main architectural components, organized into categories (e.g., arches (ARC), vaults (VLT), stairs (STR), roofs (RF), openings-windows and doors (WND/DR), walls and floors (WL/FLR), etc.). At a more detailed level, decorative elements (DCRT), such as frescoes and stuccoes (FRS/STC), as well as components of particular historical and artistic value, including liturgical furnishings (e.g., altars (LTR), pulpits (PLP), baptismal fonts (BPTM), were identified and classified, as they constitute fundamental testimonies of the site's tangible and intangible heritage. This was complemented by the identification of deterioration forms (DEG). The classification and unique coding enabled the structuring of the CDE as a standardized archive, assisting technicians in quickly locating elements, understanding their characteristics, and planning any necessary interventions. Indeed, the digitization of spaces and elements, organized according to part-whole hierarchical relationships, involved the association of a shared set of parameters. These include conservation status, chronological information, references to historical documentation and previous interventions, as well as monitoring requirements. This enables an integrated and queryable management of the HBIM model, opening up the possibility of exploring data and digital models within an AR environment, enhancing the immersive and interactive dimension of the experience.

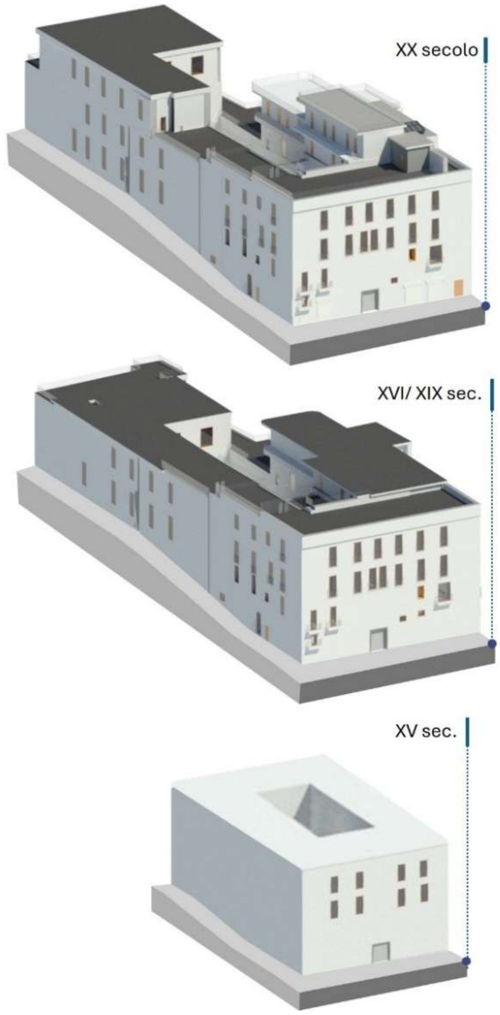

Figure 4. HBIM models representing the historical phases of the complex from the 15th century to the present.

Figure 5. Axonometric section of the complex with semantic discretization and implementation of informational parameters for spaces, elements, and components.

In particular, the integrated system required the development of an algorithm linking the informational model to digital content, conceived not merely as a communication tool but as a true information infrastructure, capable of connecting the complexity of technical data with the experiential dimension of the visit. In this way, non-specialist users can access information that is generally difficult to interpret, while professionals have an updatable and verifiable information framework useful for the knowledge, management, and planning of interventions on the heritage asset.

3. HBIM-XR Experience

The proposed workflow was designed to facilitate the integration of digital datasets within physical environments, based on an sample VPL algorithm applicable to different categories of data and structured into three main parts (Figure 6). The first segment (A) involves the rigorous collection of data from the informational model, ensuring accurate interpretation of geometric data by transforming the representation from CSG to B-Rep, as required for subsequent operations. In addition, the geometry is separated from its metadata to be synchronized with Fologram, the AR plugin, which also allows the selection of a single element to interact with via a mobile device. It is therefore necessary for the selected geometry to be reconnected to the informational element in order to manage its parameters. In this sense, the second part (B) is essential, as it performs precise data filtering, implementing identification protocols through unique IDs to ensure structured retrieval and indexing of information. Finally, the parameter management section (C) enables the dynamic manipulation of multidimensional metadata, such as Boolean or textual values, either defined directly at the algorithmic level (C1) or retrieved from the informational model (C2). This computational process was applied iteratively to various categories, ranging from architectural elements to ornamental details and material pathologies. The objective was to test the approach on different types of data, managed specifically according to their requirements.

3.1 Data Preparation and Element Identification (A and B)

The starting point of the workflow lies in data preparation (segment A of the algorithm) (Figure 6), a crucial step to ensure interoperability among the different platforms involved in the workflow. The initial requirement concerns the systematic identification of specific architectural elements to be integrated into the functional workflow; this is achieved by filtering BIM element categories and extracting the corresponding geometric representations.

During this phase, it is essential to pay careful attention to how each platform represents solid geometry. Incorrect interpretation of output formats or failure to meet the required input specifications can compromise the entire synchronization process.

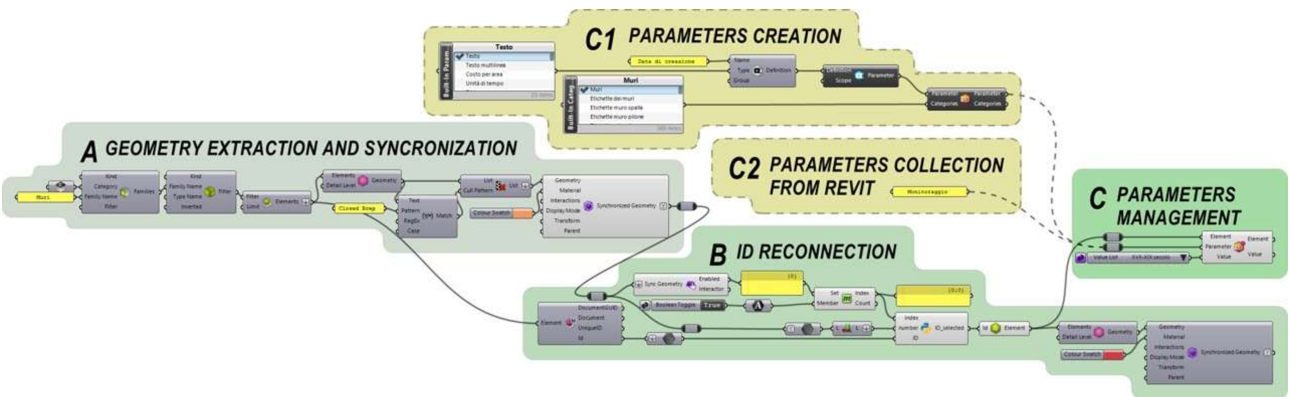

Figure 6. Sample algorithm structured for visualization of parametric-informational datasets within physical environments.

Specifically, BIM platforms typically represent three-dimensional forms as volumes using CSG, a representation model based on Boolean operations. However, to ensure compatibility with VPL languages, it is often necessary to extract these geometries as B-Rep, a model in which geometries are constructed via their boundaries. In the proposed workflow, geometric data are intentionally separated from their associated metadata to facilitate synchronization with Fologram, an AR plugin that subsequently allows the selection and manipulation of individual elements through a mobile interface.
In the AR environment, interaction is governed by an “On Hover” trigger, which makes synchronized digital objects selectable in real time via the Fologram interface. Physically moving the mobile device over a digital element or touching it generates a Boolean value that serves as a formal signal of interaction. This digital signal is sent to a “Member Index” node, which identifies the position (index) of the selected element within the list of synchronized geometries. This value then becomes the input for a custom node with a Python script, which matches the selected geometry with its corresponding unique ID, extracted directly from the list of objects in the informational model (segment B). In this way, the connection between the isolated geometry and its original informational parameters within the BIM model is reestablished, enabling real-time management and modification of parametric data via the AR interface. The element can thus be cataloged and stored again according to the coding defined in the CDE, updating values in real time. For further verification and validation of the system, the selected element undergoes a visual transformation in the graphical interface, highlighting the geometry in red. This immediate feedback serves as a diagnostic indicator, signaling that the object has been successfully recognized, indexed, and highlighted within the integrated computational system.

3.2 Metadata Implementation and Manipulation (C)

The final section of the developed algorithmic workflow represents the core of the experimentation, focusing specifically on the dynamic management and manipulation of parameters within the informational environment (C). This phase is not limited to passive visualization but enables bidirectional interaction with the objects. Through the AR interface, users can interact with the model using different input methods depending on the type of parameter being analyzed. For Boolean parameters, the AR interface provides intuitive checkboxes to define "yes/no" conditions, while for more complex data, users can select predefined values from dropdown lists, ensuring that data entry remains consistent with the established informational standards. To make these parameters modifiable in AR, it is necessary to activate the synchronization function associated with the value selector. This functionality is available for a series of nodes implemented directly via Fologram and is identified by the platform’s icon adjacent to the node itself. Synchronization is active when the icon is displayed in its original purple color (as in the first algorithm of Figure 7), and inactive when the logo appears on a gray background (as in the second and third algorithm of Figure 7).
To expand the scope of application, the proposed workflow required enhancements to provide greater flexibility in the data mapping system. Specifically, the algorithm was designed to operate on two fronts: on one hand, it can retrieve and populate parameters that already exist or were preliminarily created within the BIM environment (C2); on the other hand, it allows the creation of new parameters directly from the algorithmic workflow (C1). The object attribute database can therefore be expanded by creating new attributes and assigning names, types, and associated categories without leaving the programming environment. This approach, tested on specific categories, offers significant scalability and flexibility, allowing the informational model to be adapted to new knowledge requirements that may arise during the asset’s life cycle.

3.3 System Validation and Real-Time Model Updating

The algorithm, as constructed, was then iterated across the different tested categories and calibrated to extract, interpret, and catalog distinct informational levels, addressing specific diagnostic and management requirements (Figure 7).
Specifically, the testing phase included the analysis of chronological data, such as the “Installation Date,” particularly associated with architectural elements. For decorative elements, the need for “Monitoring” was emphasized through a parameter that incorporates prescribed maintenance requirements.
Meanwhile, for elements representing different material pathologies, a diagnostic classification was implemented, allowing precise mapping of the “Type of Degradation” and translating qualitative surveys into quantitative parameters ready for processing. The workflow is initiated via QR code (Figure 8), using an Image Target methodology that ensures precise spatial registration between the coordinate system of the physical environment and that of the virtual domain.

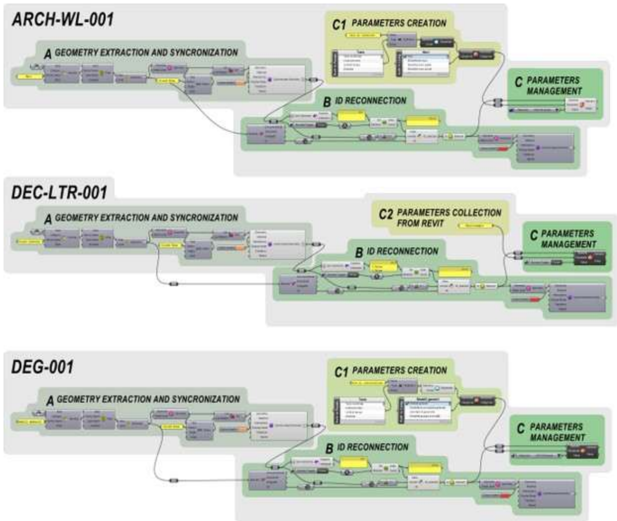

Figure 7. Algorithms designed to extract, interpret, and catalog distinct informational levels related to different categories of elements and components.

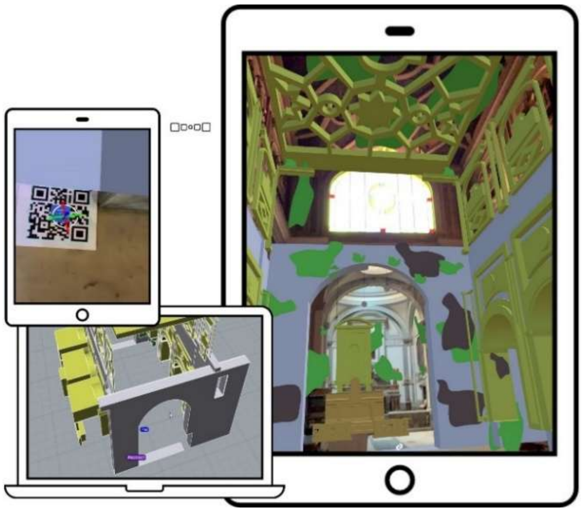

Figure 8. Spatial georeferencing between physical and virtual environments using Image Target via QR code.

Figure 9. Outcome of the developed workflow for the synchronization and/or updating of parameters associated with a degradation element.

This procedure also guarantees that the scaling of virtual elements strictly respects the metric properties of physical space. The effectiveness of the system is evident in real-time synchronization: any value updated or modified through the algorithm is instantly written into the informational model.
As an example, Figure 9 illustrates the outcome of the entire developed workflow. From left to right: the complete building model synchronized for Augmented Reality visualization through the synergy of Rhino.Inside.Revit, Grasshopper, and Fologram; in the center, the tablet view of the AR application showing the setup of the value to be assigned to a parameter associated with a degradation element. This value defines its type via a dropdown list, allowing selection among values established according to the standards set in the CDE, and is synchronized in real time with the informational model, shown on the right. This bidirectional workflow ensures that the Digital Twin remains constantly aligned with the reality of the construction site or the existing asset, making the data immediately accessible to managers and designers for planning targeted maintenance interventions, optimizing costs, and ensuring long-term structural safety. In this way, the management of the built environment is transformed into a seamless workflow, where AR technology acts as an intelligent bridge between the physical matter and its digital memory.

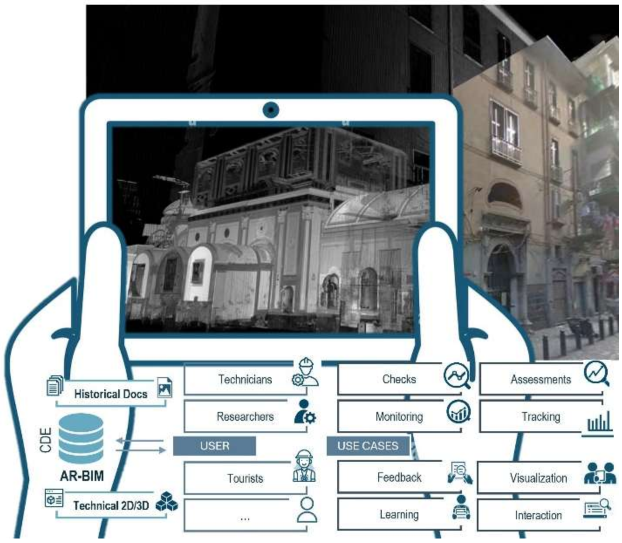

Figure 10. BIM-AR application for immersive internal visualization of the complex from the outside, for different users and use cases.

4. Conclusions and future developments

The experimentation demonstrates how the visualization of digital models in AR facilitates the understanding of historical stratifications and the monitoring of the condition of heritage sites, offering significant potential for cultural heritage dissemination. Nevertheless, the informational effectiveness of the application varies depending on the semantic discretization of the model, which requires meticulous work in structuring, data normalization, and defining an information architecture for correct migration into AR. In particular, the integration of multidimensional information and the ability to navigate simultaneously among geometry, diagnostic parameters, historical and chronological data allows not only a deeper understanding of the asset but also the development of predictive scenarios for maintenance and preventive management of architectural elements, increasing the real on-site impact of the experimentation. This approach enhances not only the real-time technical assessment of elements and components of the built environment but also the accessibility and divulgative use of the database through interactive experiences, further enabling the involvement of different types of users, from technicians to the general public, supporting immersive educational pathways, intervention simulations, and decision-making tools for heritage managers and restorers.

The possibility of customizing informational levels and AR views according to user profiles further amplifies the knowledge value of the platform, consolidating the real on-site impact of the experimentation on operational and cultural outcomes.
The quality of these experiences also depends on the ability to connect data to the real context and on the correct scaling and spatial registration of digital models. The experimentation also showed that, for the proper development of the workflow, even with satisfactory real-time synchronization results, a series of requirements—hardware, software, and network—are necessary, as their absence can destabilize the data flow. Sudden interruptions can therefore cause unexpected errors, such as visualization issues or failure to update selected values, potentially invalidating the outcomes. Nevertheless, the XR-HBIM experience remains a powerful communication tool, also allowing the reinterpretation of historical assets that are closed or partially inaccessible (Figure 10), supporting the planning of conservation interventions and dissemination, even when the tangible and intangible values of the heritage cannot be perceived from the outside. The methodology tested constitutes a replicable prototype, adaptable to different historical contexts, capable of integrating knowledge, immersive fruition, and technical management, transforming heritage management into an inclusive and sustainable digital workflow, with a clear real on-site impact of the experimentation on operational practices and conservation strategies.

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