Above-Ground and Underground Architectural Heritage Documentation: A Scan-to-HBIM-to-XR Approach for Historic Centres

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Abstract

This study presents a methodology integrating above-ground and underground 3D survey data within a Heritage Building Information Modeling (HBIM) framework, further developed into an eXtended Reality (XR) environment. The historic centre of Cagli (Italy), with its stratified architectural and archaeological layers, served as a pilot case. Data acquisition included Terrestrial Laser Scanning (TLS), UAV photogrammetry, and 3D Ground Penetrating Radar (GPR), producing detailed georeferenced datasets of buildings and subsurface anomalies. These were modeled as parametric volumes in an HBIM environment and enriched with structured metadata, including geometry, historical sources, and risk information.
The HBIM model was seamlessly integrated within an XR application built in Unity and connected with Google Cloud services, enabling real-time data exchange. Users can interact with the 3D model using a Mixed Reality (MR) headset, accessing metadata and uploading new information on-site. The system supports scenarios such as post-earthquake assessment by associating building records with standardized forms.
Results demonstrate the potential of connecting HBIM with XR not only for enhanced visualization, but also for collaborative heritage management in situ. Integration allows for intuitive, data-driven exploration of complex heritage layers, facilitating decision-making processes and opening new perspectives for monitoring, documenting, and engaging with historic urban environments. The proposed workflow is replicable and adaptable to other historic villages, which, despite their unique identities, often pose similar conservation challenges due to their layered complexity and vulnerability.

1. Introduction

The urban fabric of historic centres is the outcome of a continuous process of stratification, where visible architectures coexist with hidden, often undocumented, underground structures. This complexity presents both a scientific challenge and an opportunity for innovation in documentation and conservation strategies. The city of Cagli (Italy), corresponding to the Roman settlement of *Ad Calem* along the Via Flaminia and continuously inhabited since prehistoric times, offers an exemplary context for testing integrated digital approaches. Over the centuries, Cagli developed into a fortified medieval centre with rich architectural and archaeological layers (Luni et al., 2014). This study proposes a methodology that combines above-ground and underground 3D surveying with Heritage Building Information Modeling (HBIM) and eXtended Reality (XR), aiming to construct a dynamic, georeferenced, knowledge-based 3D model of the historic centre. Such an approach supports diachronic analysis of urban evolution while enabling informed conservation and risk mitigation strategies for public authorities and heritage managers. The methodology is grounded in recent developments in heritage documentation, remote sensing, and digital modeling that emphasize multi-resolution data integration, participatory environments, and interoperability.
HBIM is increasingly employed not only for static documentation, but as a dynamic platform for heritage protection and training purposes, as shown in (Adami et al., 2023), where the authors demonstrate how structured semantic models can facilitate specialized workflows for maintenance and education. Similarly, (La Russa et al., 2021)explore the integration between remote sensing data and City Information Modeling (CIM) to reveal and interpret the complexity of historical centres, supporting multiscale analysis from urban to architectural detail.

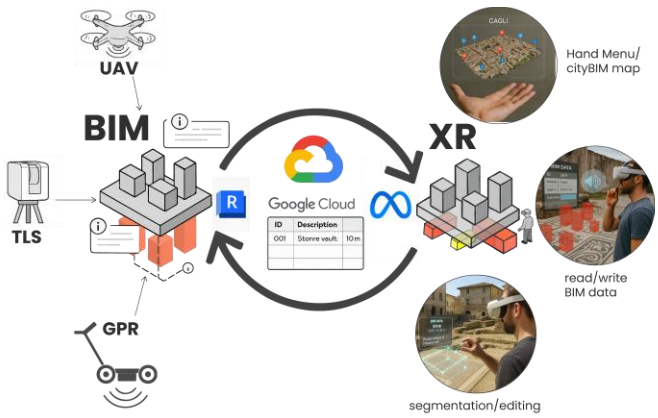

Figure 1. Collaborative workflow for real-time, cloud-enabled data exchange between BIM and XR environments.

On the subsurface side, GPR and geophysical investigations have proven effective in unveiling buried layers and voids otherwise inaccessible to conventional survey methods. The work of (Fischanger et al., 2019), for instance, demonstrates the use of electrical resistivity tomography to identify anomalies around Tutankhamun's tomb, while (Zhang et al., 2024) propose a robust method for 3D GPR imaging in dense urban environments, addressing positional uncertainties through multi-level calibration techniques. Finally, in (Ronchi et al., 2023) authors present a methodology for integrating UAV-based multispectral imagery, geophysical prospection, and archaeological excavation data into structured and reproducible 3D semantic visualizations. To connect this growing body of spatial data with immersive and interactive experiences, recent studies have begun to explore the integration of HBIM with XR platforms. (Antuono et al., 2024;

Ferretti et al., 2022; Jiang et al., 2025) present a methodological approach to augmenting HBIM with contextual, interactive experiences, enhancing architectural interpretation through mobile and head-mounted devices. (Banfi et al., 2022) further demonstrate a complete scan-to-HBIM-to-XR pipeline for the reconstruction of complex archaeological sites, emphasizing the potential of real-time exploration and collaborative data consultation in immersive environments. Additionally, recent research by (Pansini et al., 2024) underlines the importance of integrating multimodal and multi-resolution data within unified 3D environments to support a holistic understanding of historical urban fabrics. Their work on the city of Siena reinforces the notion that heritage documentation must address the coexistence of multiple spatial and temporal layers through interoperable and scalable digital frameworks.

This research aligns international guidelines such as the UNESCO Recommendation on the Historic Urban Landscape (UNESCO, 2011) which promotes the integration of heritage conservation with sustainable urban development and digital tools for heritage monitoring. Moreover, it responds to the European Commission's priorities in the European Framework for Action on Cultural Heritage (European Commission, 2019) which encourage digital innovation, open access to cultural data, and participatory approaches in heritage preservation. The New European Bauhaus initiative (European Commission, 2021) and the Digital Europe Programme (European Commision, 2021a) further emphasize the role of immersive and data-driven technologies in fostering inclusive and resilient cultural heritage strategies. Building upon these contributions, this study positions Cagli as a pilot case for a replicable workflow that connects HBIM and XR not merely as representational tools, but as an integrated ecosystem for knowledge sharing, risk prevention, and participatory heritage management.

2. Methodology

The objective of this research is to define an integrated and scalable workflow that exploits 3D survey techniques to generate an interoperable HBIM, which serves as a comprehensive and dynamic digital framework for representing both above-ground and subsurface elements of historic environments. HBIM is conceived as a central, data-rich platform that integrates geometry with descriptive, chronological, and risk-related metadata. Beyond documentation, the model is designed for active interaction through XR, allowing users to access and edit information on-site via MR interfaces. This enables real-time consultation, contextual data modification, and direct compilation of technical forms in the field.

The proposed workflow (Fig. 1) aims to bridge the gap between survey acquisition, semantic modeling, and field-based heritage management. It fosters a seamless connection between physical space and digital information, ensuring accessibility, usability, and continuity of data throughout the heritage lifecycle. Through a cloud-based infrastructure and spatial anchoring strategies, the system promotes a fluid and collaborative interaction with cultural heritage, adaptable to a variety of professional scenarios—from routine maintenance to emergency assessment. Ultimately, the research promotes a holistic, interoperable ecosystem that supports informed decision-making, encourages multidisciplinary collaboration, and lays the groundwork for new forms of heritage representation, exploration, and management in digitally augmented environments.

2.1 Data acquisition

The first phase of the proposed methodology involved the acquisition and integration of multi-source 3D data through three main techniques: 3D GPR, TLS, and UAV photogrammetry. As the surveys were conducted on different days, all datasets were aligned within a common geospatial framework based on GNSS-RTK measurements. A set of Ground Control Points (GCPs) was acquired using a Topcon HiPer HR GNSS-RTK system, referencing architecturally stable and easily recognizable features across the urban landscape. These GCPs were used as common control for the TLS, UAV and GPR surveys, enabling their integration without the need for artificial targets. All datasets were georeferenced in the WGS84 coordinate system.
The 3D GPR survey was conducted using a step-frequency Kontur GeoScope 3D-Radar system with a DXG1820 antenna operating in the 200–3000 MHz frequency range. A total of 165 radar sections, each 1.4 meters wide, were acquired with 4.5 cm spacing and partially overlapping passes to ensure full coverage. The system used RTK-GNSS positioning and an odometer for spatial referencing. The raw data were processed with Examiner™ software, applying filtering, background removal, zero-time correction, and amplitude analysis. The final output consisted of 3D georeferenced anomaly maps and polylines, which were exported in CAD/GIS-compatible formats (DWG, KMZ) and later imported into the HBIM environment. The radar successfully detected voids, buried masonry structures, and reflective layers up to depths of 2–3 meters, with anomalies interpreted based on waveform patterns and historical mapping.
The TLS campaign was carried out using a Leica RTC360 laser scanner. A total of 131 high-resolution scans were performed with a resolution setting of 6 mm at 10 m. The scans were registered using a cloud-to-cloud approach in Leica REGISTER360+, yielding an average absolute registration error of 0.003 m and a maximum error of 0.006 m, ensuring millimetric precision across the urban area. The TLS data provided dense and accurate point clouds of façades, pavements, and public spaces, serving as the primary geometry for the HBIM modeling phase.
The aerial survey was conducted using a DJI Mavic 3 Classic, which captured ~1000 high-resolution images at an average altitude of 40 meters. The estimated Ground Sample Distance (GSD) was approximately 1 cm per pixel, allowing precise reconstruction of rooftops and elevated surfaces inaccessible from the ground. The UAV images were processed using Agisoft Metashape, with GCPs derived from the GNSS-RTK survey used for accurate georeferencing. The resulting point cloud was co-registered with the TLS data, with a mean alignment error below 2 cm compared to the GCPs.

2.2 BIM implementation

Starting from the GPR data processed using Examiner™ software, returned in the form of 3D georeferenced polylines, and integrated with filtered and cleaned TLS and UAV survey models, the construction of a city-size system within an HBIM environment (Autodesk Revit) was initiated. The entire process was guided by the intention to harmonize heterogeneous data sources, originating from different disciplines (archaeogeophysics, architectural surveying, photogrammetry, and historical analysis), into a unified information model that is both spatially coherent and semantically enriched.

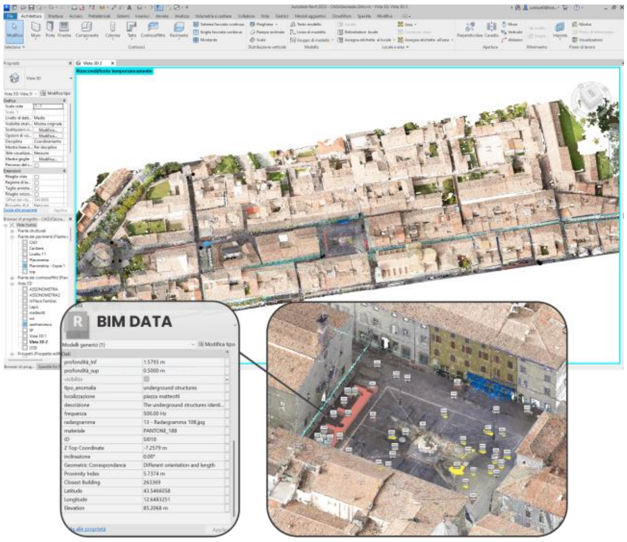

Figure 2. BIM model of the above-ground and underground architecture of Cagli. Each Ifc class is enriched with a customized dataset of shared parameters.

All elements in the model, both above-ground structures and underground anomalies, were reconstructed as simplified three-dimensional volumes, each linked to a structured set of metadata (Fig. 2). For the anomalies, the metadata includes an identification code, typological classification, estimated depth, geographic coordinates (latitude, longitude, elevation), radargram images, and interpretive descriptions. For buildings, the data includes intended use, chronology of construction and transformation phases, façade materials, conservation status, documentary sources, and any known structural risks. The choice to use a BIM environment, instead of GIS, for an urban context enabled the integration of detailed 3D reality-based models such as the tower attributed to Francesco di Giorgio Martini. Thanks to the unified 3D system integrating both the above-ground and subsurface layers of the urban fabric, and leveraging Revit’s parametric functionalities, it was also possible to automatically generate descriptive anomaly reports. These report, traditionally used by archaeologists to support interpretation, are here enriched by spatial context and include plans, cross-sections, 3D visualizations, reference images, and structured metadata. This phase represents a preliminary but fundamental step that precedes and informs the subsequent immersive XR exploration.

A distinctive feature of this implementation lies in the introduction of a set of correlation parameters (Fig. 3) specifically designed to establish semantic and spatial relationships between underground anomalies and above-ground architecture. These parameters include spatial proximity (planimetric and altimetric distance between anomalies and structures), volumetric intersections (geometric inclusion or penetration), and chronological consistency (based on historical stratigraphy and archaeological data). This allows for the emergence of new interpretative relationships, such as the potential influence of cavities or subsurface structures on the stability of overlying buildings, or the identification of pre-existing foundations compatible with documented construction phases. This approach goes beyond the traditional logic of simple co-visualization, promoting a multidimensional interrogability of the stratified urban heritage.

The adopted modeling and correlation strategy also aims to overcome one of the main challenges encountered in previous urban archaeological digitalization experiences: the fragmentation of data across different domains and tools, which often results in the creation of isolated, non-communicating information islands. In this case, however, the HBIM platform becomes a unified container, capable of hosting complex information from various domains (structural, archaeological, historical, geophysical), creating a system that is searchable, scalable, and updatable.

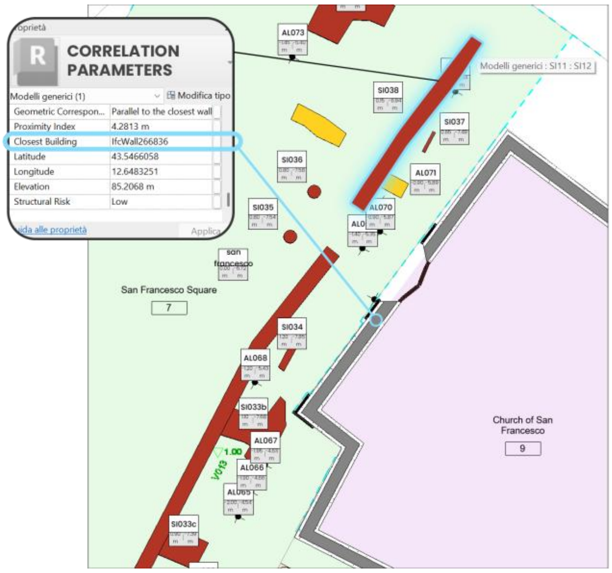

Figure 3. Plan view of the Church of San Francesco and the anomalies beneath the square. Correlation parameters such as “Closest Building” and “Geometric Correspondence” enhance the spatial contextualization of the *IfcElements* within the BIM model.

2.3 XR experience development

The development goals were defined with the intent of creating a system capable of immersive, interactive, and real-time management of information models related to built and archaeological heritage. The objective was not only to make data accessible in a three-dimensional, context-aware format, but also to provide an operational interface enabling users to view, edit, and input information directly within an XR environment, while ensuring continuous synchronization with the original HBIM model. This vision addresses the growing need to integrate immersive tools into heritage documentation, monitoring, and valorization workflows, bridging the gap between design environments and visualization tools.

To this end, a mixed reality (MR) experience was developed, establishing direct communication between the HBIM model, created in Autodesk Revit, and an immersive scene built in Unity 3D. To guarantee a continuous and bidirectional data flow between platforms, an interoperable workflow based on Google Cloud APIs was implemented. Specifically, Google Drive was employed for managing 3D files, images, and JSON annotations, while Google Sheets handled the transmission and synchronization of alphanumeric data linked to model elements. This distributed cloud-based approach overcomes the limitations of local or monolithic systems and enables scalable, collaborative, and mobile-friendly management of heritage datasets.

Interoperability is achieved through the development of custom plugins (Fig. 4): a Python component operating within Dynamo for Revit, and a C# component integrated into the Unity XR application.

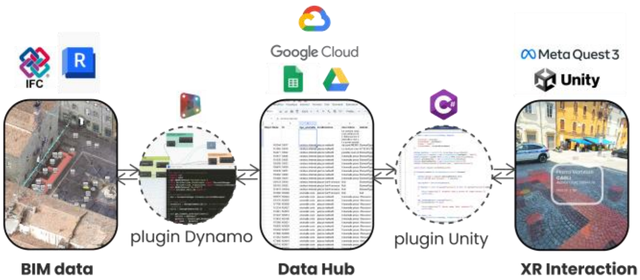

Figure 4. Continuous communication between the BIM and XR environments through Google Cloud is maintained using visual programming tools such as Dynamo for Revit data processing, and C# scripting within Unity for data integration and interaction.

The Dynamo script extracts geometry and parameter data from HBIM elements and sends them to a structured Google Sheet through a dedicated Web App endpoint. The script ensures a one-to-one match between model objects and spreadsheet rows via a persistent UUID system, enabling seamless synchronization between BIM and XR environments. In parallel, Unity’s C# module dynamically reads spreadsheet data and related files from Google Drive, associating them with corresponding virtual objects in the immersive scene. This allows users to wear a Meta Quest 3 headset to interact with BIM content in real-world space: viewing, updating, or annotating objects with voice or gesture commands. Alphanumeric changes are immediately propagated back to the central database and the HBIM model, preserving data integrity and operational consistency across the system. In addition to parameter data, the system also supports the automatic export of reference images for BIM elements. These images, generated within Revit and organized via Dynamo, are uploaded to structured folders in Google Drive, where they can be linked back to the corresponding XR objects during interaction. This allows inspectors and field operators to cross-reference visual and descriptive information, increasing situational awareness and traceability.

Meta Quest 3 was chosen for its balance of performance, mobility, and affordability. It offers six degrees of freedom (6DoF), environmental tracking, and persistent spatial anchoring without external hardware. These features allow precise positioning of virtual content in the physical world. The headset’s native hand-tracking capabilities enabled the development of a fully touchless interface, while its built-in microphone allowed for seamless voice dictation. The entire immersive experience was developed in Unity 3D using standard Meta XR SDK assets. Content integration and application logic were handled through custom C# scripts developed in Microsoft Visual Studio, enabling real-time interaction, data access, and UI generation within the immersive scene.

Each virtual object in the scene is linked to a unique UUID, guaranteeing a persistent connection to a specific row in the external Google Sheet. This structure supports real-time synchronization and ensures that updates to data made in the XR interface reflect immediately in the BIM database. In “read/write mode”, when a user selects an object, a raycast retrieves the UUID, and a GET request is sent to the Web App, which returns the corresponding attribute data. The data is parsed and displayed as editable fields using dynamically generated *TextMeshPro* elements, allowing users to view and modify object parameters directly within the scene. Voice dictation enhances this interaction: users can click on any editable field and dictate the new value. A dedicated script captures the dictated text, populates the correct field, and flags it for submission. Once the editing session is confirmed, a structured POST request is sent back to the Web App, updating only the modified cells while preserving alignment between the XR content and the BIM model. Beyond data editing, the application features a “segmentation/editing” mode that allows users to annotate the environment with spatial markers. Point-based tags and polylines can be created to indicate specific conditions such as collapse, restricted access, or material degradation. Each annotation can be enriched with metadata including descriptive text, reference images, urgency levels, or document links. Annotations are stored in a structured JSON format, including fields such as UUID, type (point, polyline, or polygon), coordinates (in world space), timestamp, and metadata (e.g., "description", "category"). This standard ensures cross-platform interoperability and clear semantic definition of spatial information. These JSON files can be imported into the BIM environment using a dedicated Dynamo script. The script reads the annotation data, reconstructs its geometry (as lines, areas, or volumes), and generates 3D representations using the *DirectShape.ByGeometry* node. Depending on their nature, these elements are classified with appropriate IFC types—such as *IfcAnnotatio*n or *IfcBuildingElementProxy*—and enriched with the original metadata to preserve semantic integrity. As a result, annotations created in XR become permanent, queryable components of the HBIM model.

Figure 5. By setting the read/write mode it is possible to display and edit the information associated with the BIM platform. Based on the selected object, the related data is dynamically displayed within the interface. Each parameter can be edited through voice dictation. Once the editing process is completed, the updated content is first sent to Google Cloud and subsequently synchronized with the local BIM model.

Since Meta Quest 3 lacks native GPS, an external solution was developed to enable georeferencing. The headset connects via Wi-Fi to the user’s smartphone, leveraging the phone’s GPS signal to obtain real-time coordinates. This system serves multiple purposes: annotations and events can be anchored to precise real-world locations, while GPS positioning also enables automatic loading of the correct virtual scene depending on the user's physical location. For instance, when entering Piazza Matteotti or other key sites, the application identifies the position and activates the relevant virtual environment, aligned with spatial anchors placed across the urban context. This ensures millimetric precision and spatial continuity between physical and digital layers of the city model.

To support this system of multimodal interaction, three types of UI interfaces were developed: a hand-referenced menu is activated when the user opens their left hand, this interface follows the movement of the palm and provides access to core functionalities such as data read/write, annotation tools, segmentation, and mode switching. It also includes a 3D map of the city, showing the user's position and highlighting key points of interest. This menu serves as the primary control dashboard for interacting with the entire BIM dataset. The object-referenced interface is designed to appear above or near selected BIM objects (Fig. 5). This UI displays object-specific attributes in real time. Panels are dynamically oriented toward the user to ensure readability, and each parameter can be edited via voice dictation. Once confirmed, changes are first updated in the cloud (Google Sheets) and subsequently synchronized with the HBIM model.
Finally, the camera-referenced interface is anchored to the user's head movements (Fig. 6). This floating panel is context-sensitive: it activates automatically when the user enters different city zones, displaying the name of the area (e.g., street or square) and listing associated BIM objects, both above and below ground. This enhances spatial awareness and supports real-time contextual interaction.

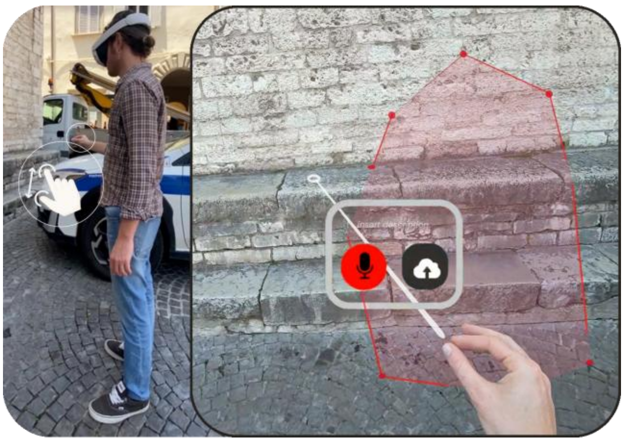

Figure 6. By selecting the segmentation/editing mode, it is possible to create areas, volumes, or empty objects directly in the real environment, thanks to the superimposed virtual model of the city (including buildings and terrain), which is equipped with an invisible occlusion material. A UI interface, referenced to the camera view, automatically appears to enable voice dictation for comments and, if required, send the new data to the cloud in JSON format.

3. Results

The main outcome of this research is the successful integration of Terrestrial Laser Scanning (TLS), UAV-based photogrammetry, and 3D Ground Penetrating Radar (GPR) data within a coherent HBIM environment. This integration enables direct correlation between above-ground architectural structures and subsurface anomalies, thus expanding the interpretive capacity of the model beyond visible features. Detailed analysis of the 3D radargrams has revealed significant buried structures in strategic areas of the historic center, such as wall foundations, paved surfaces, and underground voids. These features likely correspond to former civic, religious, or defensive constructions and are often corroborated by historical maps and archival sources. Additionally, reflective surfaces consistent with ancient floors were identified at different depths, suggesting the presence of a complex and stratified urban subsoil. The structured information model created through this workflow supports advanced heritage management tasks, including scenario-based simulations, stratigraphic reconstruction, structural vulnerability analysis, and immersive interaction via XR platforms. The system's ability to integrate heterogeneous data sources allows users to perform dynamic and thematic queries, for example, filtering anomalies by construction phase, typology, or geotechnical characteristics. In this way, the HBIM model transcends its traditional role as a static information container and becomes an active interpretive tool, capable of representing the multilayered and diachronic complexity of historic cities through explicit, queryable relational logic.

The approach was validated in a real-world case study focused on the management of a stratified archaeological urban context. In this environment, each information object, whether a building, a subsurface anomaly, or a fragment of architectural structure is associated with metadata sheets that can be accessed and edited directly within the XR interface. This allows users to interact with elements in situ, review relevant documentation, and update information in real time during inspections, field surveys, or restoration operations. The platform supports not only data consultation but also context-aware data input, which is particularly valuable in emergency or maintenance scenarios. For example, following an earthquake event, each building can be linked to a digital version of the AeDES (Post-Earthquake Damage and Safety Assessment) form, which can be filled out by technicians directly in the MR environment. This capability provides immediate access to spatial context and historical/structural data, improving both the accuracy and timeliness of condition assessments.

The system enables full integration between the HBIM model and immersive XR experiences, effectively overcoming the fragmentation of data and workflows. It fosters a participatory and operational approach to cultural heritage management, supporting professionals, institutions, and stakeholders in the monitoring and preservation of historic assets (Fig. 7).

4. Conclusions

The presented research represents a substantial contribution to the management, documentation, and enhancement of stratified urban heritage by effectively integrating advanced 3D surveying, HBIM, and immersive XR environments. Applied specifically to the historic center of Cagli, this methodology illustrates the potential of combining digital technologies and multidisciplinary expertise to develop innovative ways of representing, understanding, and interacting with CH, capturing its historical, material, and spatial complexity comprehensively. At the core of the proposed system is an interoperable ecosystem that combines MR with structured information models, enabling seamless interaction between real-world contexts and digital data. The adoption of a touchless, spatially anchored interface supports a range of user needs, from simple data consultation to real-time editing and in-situ compilation of technical forms. Associating each object with rich descriptive, chronological, and spatial metadata fosters a dynamic interpretive framework that enhances both conservation workflows and emergency response strategies.

A key strength of the approach is its ability to maintain real-time, bidirectional synchronization between the XR environment and the HBIM model via cloud infrastructure. This enables not only collaborative and distributed data management but also supports scalable operational scenarios adaptable to other heritage

Fig. 7 a) GPS referencing via smartphone; b) UI hand-referenced interface displaying the Cagli BIM model with buttons to select features: data read/write, segmentation/editing, and VR mode; c) Visualization of anomalies; d) Visualization of above-ground architectural BIM data with the AEDES sheet for seismic assessment; e) Visualization of underground architectural BIM data; f) Creation of new spatial areas in the real environment.

contexts. Gesture-based navigation, voice command input, and real-time geolocation further improve usability, making the system ergonomic and practical for professionals operating in the field.

Looking forward, the system's future development includes expanding semantic parameters and incorporating artificial intelligence analytical tools to automate the assessment of relationships between subsurface anomalies and above-ground structures. Such advancements promise to enhance the system's utility as a decision-support platform, facilitating diagnostic evaluations, preventive measures, and historical-interpretive analyses. However, the reliance on constant online connectivity poses potential challenges. Continuous live data exchange demands substantial bandwidth and robust data management strategies, potentially impacting the smoothness and responsiveness of user interaction, particularly in contexts with limited network reliability or lower data-transfer capabilities. The system's fluidity of use could thus be constrained by these connectivity requirements. Addressing these limitations transparently adds credibility and robustness to the research outcomes by clearly outlining both the technological benefits and practical challenges associated with real-time connectivity.

In summary, this research underscores how the strategic application of XR technologies within a coherent and integrated informational framework can introduce innovative modes of interacting with heritage assets. This approach fosters an urban management culture characterized by active participation, transparency, and collective intelligence. The interoperability, accessibility, and real-time update capabilities inherent to the proposed model provide a solid foundation for developing increasingly interconnected, dynamic, and integrated urban information systems.

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