IMMERSIVE CONSERVATION: INTERACTIVE TOOLS FOR PRESERVING BUILT HERITAGE

Y. Patankar[1], D. Mitterberger[2], B. Bomou[3] and R. J. Flatt[4]*

Abstract

The conservation of stone-built heritage presents unique challenges, ranging from documenting complex geometries and understanding the underlying damage mechanisms to implementing conservation strategies. Addressing these challenges requires a comprehensive methodology involving a multidisciplinary team of stakeholders and experts, monitoring tools, and impact assessments. Recent advancements in Heritage Building Information Modelling (HBIM) offer novel solutions for the integration of datasets from multiple disciplines to enhance collaboration among experts. However, HBIM models are often complex, static, and not connected to real-time data, limiting their applicability to a single case study and preventing broader use across multiple contexts. Extended Reality (XR) technologies offer much-needed solutions for enhancing visualisation and intuitive engagement with these models.

This paper introduces a novel framework that combines HBIM and XR to address stone conservation challenges. HBIM serves as a robust platform for 3D modelling and data integration, while XR enables spatial visualisation and interactive engagement, facilitating both on-site and remote expert consultations. The preliminary framework is developed for a reference monument, the Lausanne Cathedral. This integrated approach can foster collaboration across disciplines, allowing stakeholders to access the information in the HBIM model, and overcoming the compartmentalisation of data.

Keywords: Heritage Building Information Modelling (HBIM), Extended Reality (XR), stone characterisation, multidisciplinary collaboration, intuitive interaction.

1. Introduction

Historic structures undergo complex degradation processes driven by an interplay of interconnected factors. Restoring built heritage is essential for ensuring their long-term preservation (Hajirasouli *et al.,* 2021). These projects involve multidisciplinary professionals, continuous on-site monitoring, and periodic impact assessments. The deterioration of building materials, specifically stone, results from intrinsic and extrinsic influences (Rives and Garcia-Talegon 2006; Winkler 1973). At the monument scale, factors such as the location, orientation, and exposure of structural elements to microclimatic conditions lead to an uneven distribution of deterioration patterns and alteration rates. Hence, a universal solution is rarely effective, necessitating tailored interventions based on specific conditions (Scherer *et al.,* 2001). Therein, a reliable spatial understanding of the monument in question is crucial for assessing damage mechanisms.

Effective restoration requires multidisciplinary collaboration among architects, engineers, and historians. Stakeholders often work independently, leading to fragmented data and inefficiencies such as duplicated efforts and overlooked existing information (Penjor *et al.,* 2024). Additional challenges arise due to the complexity and diversity of heritage data sources, which can hinder effective communication and collaboration among experts from different disciplines (Van Balen 2017). One way to address these challenges is through visual storytelling, particularly interactive visualisations, which can enhance comprehension and usability for all stakeholders (Zawarus 2023).

In this context, integrating spatial computing technologies with traditional conservation methods presents promising perspectives. Spatial computing encompasses a range of technologies that merge the physical and digital worlds, including AI, mobile computing, XR, and more (Yenduri *et al.,* 2024). These tools transform user interfaces (UI), shifting from

[1] Yamini Patankar, Doctoral student, Institute for Building Materials, ETH Zurich, Switzerland, ypatankar@ethz.ch

[2] Daniela Mitterberger, Assistant Professor, School of Architecture, Princeton University, New Jersey, United States of America, mitterberger@princeton.edu

[3] Brahimsamba Boumou, Scientific Collaborator, Geopolis, Institute of Earth Sciences ISTE, University of Lausanne, Switzerland, brahimsamba.bomou@unil.ch

[4] Robert J. Flatt, Professor, Institute for Building Materials, ETH Zurich, Switzerland, flattr@ethz.ch

* Corresponding Author

conventional screen-based interactions to immersive, spatially aware experiences that blur the boundaries between virtual and real environments (Cao 2024). The integration of these technologies in conservation practice can provide an accessible digital tool that allows data retrieval and visualisation during on-site inspections, reducing the need to switch between field and office environments (Patankar *et al.,* 2024).

2. Literature review and the state of the art

2.1 Stones properties

The degradation of building stones is influenced by both intrinsic and extrinsic factors, as outlined in Section 1. As successfully showcased by the study of Piovesan *et al.* (2023), analysing and visualising the intrinsic properties of stones alongside geometry, degradation patterns, and microclimatic data (by mapping), help identify degradation mechanisms and inform targeted conservation strategies. The physical and chemical properties of stones, alongside mineralogy and petrology, largely determine their durability. The petrology and mineralogical composition affect resistance to physical and chemical degradation, with key factors including porosity, pore size distribution, mineral solubility, susceptibility to dissolution and chemical erosion (Rives and Garcia-Talegon 2006). Identifying the mineral composition can contribute crucial insights for diagnosing deterioration mechanisms and informing conservation strategies. For instance, in certain sedimentary rocks, a calcite or clay matrix can promote crack propagation, while more rigid minerals like quartz and feldspar remain largely unaffected (Tiennot *et al.,* 2019).

In its initial stages, this project relies on characterising mineral composition by quantitative X-ray Diffraction (XRD) and using Scanning Electron Microscopy (SEM) to evaluate its microstructure. More detailed investigations are planned but not reported here. The mechanical properties of a stone determine its ability to withstand external forces and environmental stresses. While compressive strength is most generally measured, tensile strength is most often of greater importance in terms of durability (Siegesmund and Dürrast 2014). Other important factors are the Modulus of Elasticity and how this may change between wet and dry states for clay-bearing stones (Scherer and Gonzalez 2005).

2.2 Tools for documentation and visualisation in heritage conservation

The advent of digital technologies in heritage preservation introduced tools such as digital photogrammetry, laser scanning, LiDAR, and UAVs, which enable high-precision 3D mapping and comprehensive aerial documentation of heritage sites. On the other hand, computer-aided design (CAD) facilitates the creation of detailed virtual 3D models and digital twins (Preti *et al.,* 2019; Verma and Yadav 2023). More recent advancements integrate multiple technologies, including infrared imagery, photogrammetry, ground-penetrating radar (GPR), and microwave measurements, to provide a holistic representation of architectural, material, and structural elements (Adamopoulos *et al.,* 2021). HBIM plays a key role in these workflows, combining point cloud data from 3D laser scans, historical archives, and non-destructive testing (NDT) to support multidisciplinary collaboration and informed decision-making (Tennenini *et al.,* 2023). In recent years, emerging tools like XR, and AI have been explored for their potential in the preservation of built heritage.

2.2.1 Heritage Building Information Modelling (HBIM)

HBIM, a concept introduced in 2009, integrates BIM with heritage preservation, offering a structured approach to documentation and data management (Murphy *et al.,* 2009). Early research focused on parameterising architectural elements and reconstructing geometries from point clouds (Gámez Bohórquez *et al.,* 2021), while recent studies explore HBIM for site monitoring of moisture distribution (Pocobelli *et al.,* 2018). However, managing both static and dynamic datasets collaboratively remains a challenge (Jouan and Hallot, 2020). Extensive digitisation efforts across Europe are now driven by various cultural heritage initiatives. Banfi's work on Scan-to-BIM and XR adaptation has enabled immersive museum tours (Banfi 2021; Banfi and Oreni 2020; Oreni *et al.,* 2024), while Biagini *et al.* (2021) examined BIM-based immersive visualisation in historic spaces. Recent studies applied HBIM and 3D laser scans to model the Ghiqa Historical Market, capturing architectural, structural, and material attributes for structural analysis, condition assessments, and historical data integration (Baik 2024). A review by Penjor *et al.* (2024) highlights the increasing use of HBIM since 2020 for documentation, analysis, visualisation, and plugin development.

To enhance impact, a centralised platform is needed for integrating and visualising data across scales and timelines, from monument-wide assessments to material-level analysis. Effective collaboration requires multidisciplinary connections, data accessibility, and continuous updates for real-time monitoring and adaptation. However, HBIM platforms remain complex, limiting accessibility. Future methodologies should shift from static, "screen-locked" content to interactive, "world-locked" experiences (Vtieto 2022), making heritage data more engaging and widely accessible.

2.2.2 Immersive tools for heritage conservation

XR encompasses Augmented Reality (AR), which overlays digital information onto real-world objects, and Virtual Reality (VR), which creates fully immersive digital environments (Cao 2024). While many studies have explored integrating AR and VR with HBIM, most applications focus on tourism rather than conservation. This overlooks their potential for interactive documentation, storytelling, and visualising lost or at-risk heritage elements (Banfi and Oreni 2020). XR platforms are also emerging for large-scale heritage visualisation, enabling virtual site visits and remote engagement (Pervolarakis *et al.,* 2023). Some projects, such as Bolognesi and Fiorillo (2023), develop immersive VR environments for cultural heritage, prioritising accessibility with user-friendly tools for interaction and annotation. Shared digital platforms also facilitate continuous heritage monitoring, allowing professionals to track degradation and plan maintenance through environments like Unity Reflect. The Heritour project advances this approach by integrating real-time survey data into a risk preparedness system, supporting hazard monitoring, risk mitigation, and informed conservation strategies through immersive XR experiences (Mezzino and Arena 2024).

Improving XR accessibility for diverse users remains a challenge, with ongoing efforts to develop intuitive interfaces (Bolognesi and Fiorillo 2023). While current AR and VR applications in heritage primarily enhance tourism through immersive museums and virtual tours (Rodriguez-Garcia *et al.,* 2024), their potential extends to conservation. Future developments could focus on collaborative visualisation for structural and material analysis, integrating microclimate and degradation data into AR/VR projections. This would enable remote consultations and interdisciplinary collaboration, shifting these technologies from passive experiences to practical problem-solving tools for heritage conservation.

3. Methodology

3.1 Framework- immersive conservation

This project develops a structured workflow for data input, storage, and visualisation of critical material and archival information. The project builds on the COMPAS XR framework, an open-source geometric modelling and XR visualisation tool that primarily focuses on AR-enhanced and robot-assisted workflows. The framework ensures flexibility, scalability, and compatibility across different HBIM and XR platforms, and hence, some parts of the pipeline are adopted in this workflow (Mitterberger *et al.,* 2024). As depicted in Figure 1, a central cloud-based database is organised to store static and updatable datasets, including 3D geometry, archival photographs, technical drawings, condition assessments, and material characterisation reports. It is designed for expansion, allowing additional sources to be integrated as needed. Datasets are dynamically retrieved from cloud-based storage solutions like Firebase and linked to both the BIM model and Unity environment via API connections. This ensures seamless interoperability, making the central database accessible to both HBIM and XR applications. To enhance data retrieval, keywords are embedded within the BIM model's geometry as parameters as a primary dataset, allowing structured and efficient access to interconnected information. This streamlines a two-way workflow between Revit and Rhinoceros (CAD environment) for BIM modelling and Unity Engine for visualisation and interaction.

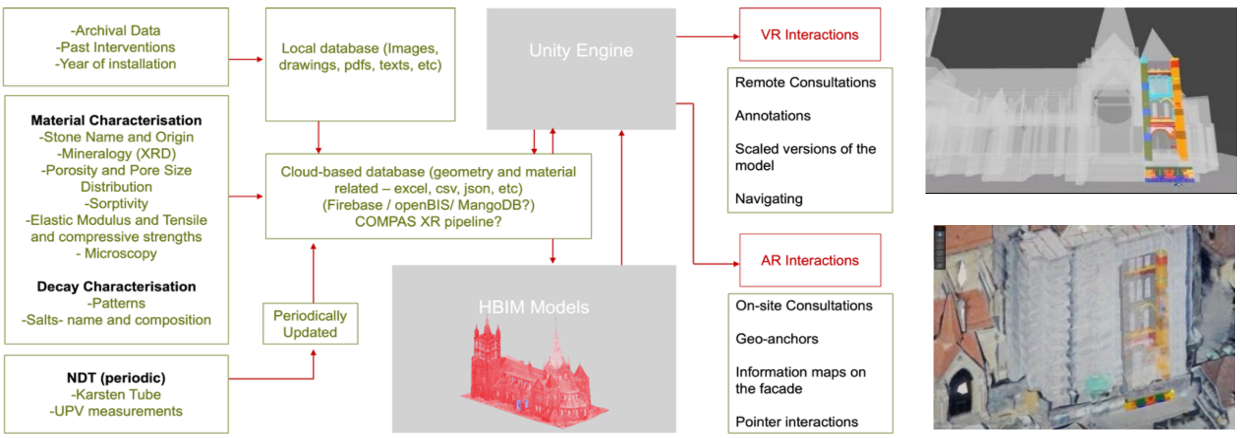

Figure 1: Framework for immersive conservation, from data collection to immersive interactions.

Additionally, external datasets (also referred to as secondary datasets) detailing stone durability properties are stored in Firebase as JSON and CSV files. These datasets include mineralogical and geochemical compositions, microscopy results (Hughes 2017), XRD mineralogical analysis, and elemental composition from X-ray fluorescence (XRF). Further integration includes petrological, physical, and mechanical characteristics from both laboratory and on-site tests, complemented by insights from existing literature. Historical data on stone age and past interventions introduces a temporal dimension, linking conservation history to material analysis. This central database enhances XR applications by transforming them from static object visualisation into interactive visualisation of systems. Archival images and drawings are also mapped into the BIM model to provide historical context and add to the knowledge base. Finally, Unity is used to visualise this geometry and information and create intuitive interactions in both AR and VR.

4. Case Study- first steps

Lausanne Cathedral was selected as the reference monument for this study due to its historical significance, complex geometry, and structural intricacy. Constructed in the 12th century, it is one of Switzerland's largest Gothic monuments and a key European heritage site (Villes 2012). The cathedral's structure comprises various stone types, reflecting centuries of interventions and restoration efforts (Huguenin 2012). These material variations, combined with diverse microclimatic conditions, have led to differing rates and patterns of degradation. This section outlines the implementation of the Immersive Conservation methodology for this monument.

4.1 Information structuring

As this is the initial part of the project, limited datasets are integrated at this stage. A working dataset is derived from the petrological analysis of the stones of the cathedral, with (Bomou and Adatte n.d.) serving as a baseline report. The data is structured into a primary and a secondary information set. The primary set is directly attached to the HBIM geometry, including stone names, origin, age, installation period, and classification. It remains static, with occasional updates following new interventions and is formatted as JSON to maintain structured data accessibility. The secondary set is queried and retrieved as needed, containing expanded datasets such as mineralogy reports, SEM images, tomography results, and video documentation. This secondary dataset is frequently updated with chemical and physical analyses, NDT results, and supplementary archival materials. A key challenge involves systematically structuring and maintaining the secondary dataset to ensure periodic updates and accessibility for all stakeholders, including non-specialists.

4.2 HBIM and data integration

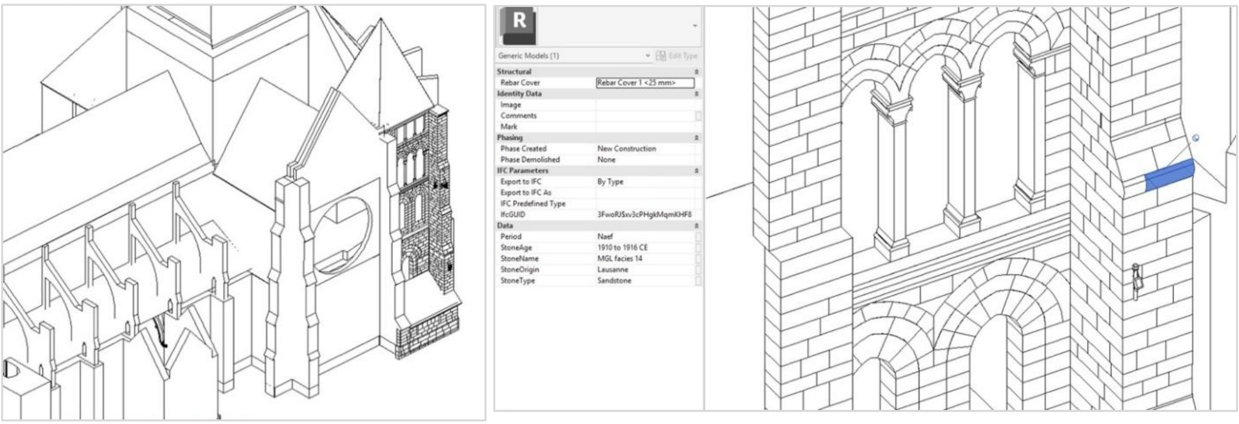

Figure 2: HBIM model of the Lausanne Cathedral with primary datasets.

The first step in developing an immersive data model is integrating relevant databases with 3D geometry using HBIM. For the Lausanne Cathedral, this involves constructing a digital model from point cloud and photogrammetric sources, embedding both high- and medium-precision geometric details along with distinct, identifiable elements. This ensures a comprehensive framework tailored to conservation needs. Geometric modelling was conducted in Rhino, while Revit served as the BIM authoring tool. The Rhino. Inside plugin facilitated seamless integration between both platforms.

A block-by-block 3D model was developed for the South Tower of the transept, a section undergoing recent conservation efforts. Since the 13th century, this façade has featured various stone types, prompting intensive studies on lithology, mineral composition, condition assessment, and architectural history. Material information was assigned to individual blocks using a semi-automated Dynamo workflow in Revit. The enriched model was then converted into a graph-based COMPAS data structure, with geometry and attributed data uploaded to Firebase in JSON format via API. This preliminary information can be retrieved in Revit as parameters or in Rhino as attributes.

4.3 Immersive interactions

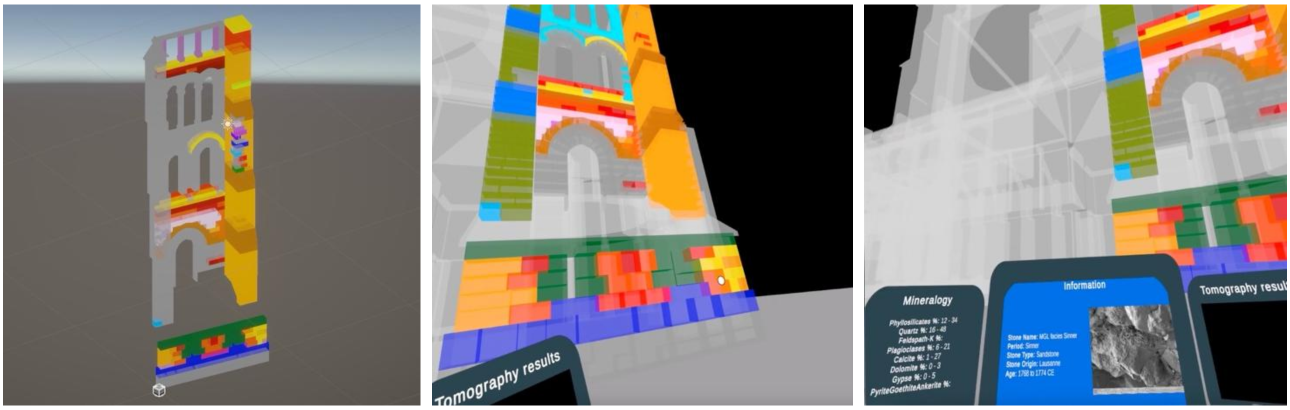

Figure 3: Interactions and interfaces in VR mode.

A crucial challenge is enabling users to actively engage with the data model rather than simply viewing static visualisations. Conventional AR overlays typically provide minimal interactivity, treating physical environments as passive canvases rather than dynamic interfaces. However, advancements in Human-Computer Interaction (HCI) and XR allow for more seamless and intuitive interactions, fostering a deeper connection between users, built heritage, and data. Unity is used to develop both AR and VR applications. The AR workflow involves reconstructing meshes by parsing JSON files containing geometry (vertices, faces) and attributes. The meshes are filtered based on stone type, period, origin, and classification. Finally, interactive maps generated from material information are visualised onto the real-world monument, spatially linked via geospatial anchors or object recognition provided by ARKit and ARCore. This allows stakeholders to access relevant information on-site, interacting with data in situ. While challenges remain, such as anchor accuracy and reliance on device positioning and camera, geospatial anchoring for AR presents significant potential for on-the-fly data visualisation, thereby increasing the quality of interdisciplinary dialogues.

VR visualisations provide solutions for remote consultations, allowing off-site access to the HBIM model and related datasets. This enables immersive 3D analysis and collaborative conservation planning. Given the current limited availability of AR devices, VR also serves as a placeholder for testing interactions within the data model. For this project, Meta Quest 3 was used to develop a VR prototype. An extendable UI panel was anchored to the controller, allowing users to directly interact with the 3D model, retrieve stone-specific information by pointing at blocks, displaying attributes such as stone type, age, and petrology, and view SEM analysis results as images and tomography results as videos. These interactions demonstrate the potential for XR-driven impact assessments, which are critical for conservation decision-making. As the project advances, integrating geometric and material information with rainwater management data, weather patterns, and video documentation of rain events will enhance predictive analysis of degradation processes.

4.4 Conclusions and future work

Heritage conservation can benefit from intuitive interactions with spatial and material data through emerging technologies. AR enables efficient on-site consultations by overlaying structural, material, and weather data as interactive maps, while VR facilitates remote collaboration by providing immersive 3D exploration. This paper explored an immersive conservation workflow, outlining essential data types and their visualisation methods across different interaction modes, as part of the broader Heritage++ initiative. However, key challenges remain, due to the limitations of HBIM, which, as an extension of BIM, struggles with customisation, heritage-specific data parameters, and maintenance complexity. Additionally, the diversity of heritage sites and limited datasets hinder purely data-driven approaches, making it essential to blend traditional expertise with technological advancements. Some technological challenges arise due to limited tools available for AR experience. Hence, interactions are mainly being explored in VR, to be later transferred into AR mode. Future work will focus on refining methodologies, expanding data integration, improving immersive interactions and UIs, and conducting user studies and evaluations to enhance the effectiveness of these technologies.

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