# ARCHITECTURAL HERITAGE DIGITAL REPRESENTATIONS FOR CONSERVATION STRATEGIES

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**KEYWORDS:** Architectural Heritage, digital representation, scan-to-BIM, HBIM, conservation and management process.

## ABSTRACT:

Digital technologies enable a thorough analysis of Architectural Heritage, offering various representations that provide different levels of documentation and knowledge-based conservation tools. This paper presents a methodological approach that leverages three digital representations related to three levels of documentation: Virtual Tour Informational Modelling, Point Cloud Informational Modelling, and Historical Building Information Modelling. Their characteristics and potential are compared, focusing on the effectiveness in supporting the analysis process, and the management of future conservation works. Furthermore, the dichotomy between 2D and 3D representations of AH is tackled, emphasizing the need to align with the conservation strategies, timeline, and budget constraints. It also discusses the integration of heterogeneous data and various digital representations to address the challenges in AH preventive conservation and management, resulting in the proposal of a sustainable documentation workflow to support the conservation process.

## 1. INTRODUCTION

In the field of Architectural Heritage (AH) documentation, there is a dichotomy between 2D and 3D representations. Both approaches are useful in supporting preventive and planned conservation, conveying different data relevant to building management challenges. Currently, 2D methods, such as digital mapping, written reports, and images, are often used for initial documentation, providing a broad overview of a building's condition and historical phases. On the other hand, 3D methods are more commonly exploited to support in-depth analysis of a building's consistency, capturing the full complexity of an AH that requires a high level of detail (LOD) according to Building Information Modelling (BIM) standards (AIA, 2013). However, they require specialized equipment, expertise, and additional processing time compared to 2D methods. So, it is crucial for the sustainability of conservation strategy that the representation method aligns with the project scope, timeline, and budget constraints. Additionally, it is important to consider that AH management challenges are constantly evolving. Combining data acquired at different times and by different methods is a key issue for process efficiency. [PC]

### 1.1 Preventive and planned conservation strategies for Architectural Heritage

Since its establishment, the discipline of restoration has always been an interpreter of the historical, cultural, and social demands of the present. While upholding key principles – such as distinctiveness, compatibility, minimum intervention, durability, and reversibility –, the way in which historic buildings and sites are treated has changed over the centuries, and attitudes and practices have been rethought. After the Second World War, the restoration culture was critically updated, focusing on the relationships between time, nature, material, and memory. This update gradually emphasized the co-evolutionary dimension of heritage concerning its context and the aptitude of heritage for adaptive change. Thanks to the positions held by important figures in the Italian restoration scene, Cesare Brandi and Giovanni Urbani, the concepts of 'preventive restoration' and 'preventive and planned conservation' were established (Brandi, 1956; Urbani, 1973). Both concepts address the issue of the 'long term', embracing the idea that preserving heritage does not mean freezing it, but managing its transition across generations (Della Torre, 2021; Petraroia, 2022).

The complexity of cultural heritage arises mainly from its existence over time, rather than its ability to exist exclusively in a historical phase that is often mistakenly assumed to coincide with the date of its construction (Ferlenga et al., 2008). The practical implications of these theoretical achievements can be traced in the shift from a project-oriented to a process-oriented vision in heritage conservation, as well as from an approach that remedies damages to one that minimizes the risk of damage as much as possible (Vandesande et al., 2018). Managing the 'system-object' relationship and interaction is crucial, especially in the case of open-air historical architectures, such as archaeological sites, both ancient and modern.

Therefore, the most promising and challenging strategy is the long-term planning of continuous care, based on the integration of conservation, preservation, and management activities for architectural heritage. It is important to emphasize that such an approach to heritage presupposes a precise and constantly updated knowledge of the asset in question. International experts at ICOMOS have recognized knowledge-based actions and tools as the primary qualifying elements for interventions with potential impacts upon cultural heritage (Dimitrova et al., 2020).

From this perspective, advanced digital technologies offer opportunities for experimentation that can support the goal of preventive and programmed conservation (SIRA, 2023). They enable the semantic organization of cultural contents, the integration and consultation of data, and interaction among different stakeholders. Recording data effectively serves multiple purposes for safeguarding cultural heritage. These include assessing values and significance, providing scientific support for interventions, documenting heritage under threat from natural or anthropogenic causes and post-disaster,

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supporting intergenerational continuity, disseminating knowledge about the heritage site and its history, including the creation of digital storytelling products through such means as virtual tours, virtual and augmented reality (De Vos et al., 2023). It is undeniable that these operations are time-consuming, but they are necessary to ensure the sustainability of conservation actions throughout the entire life cycle of the cultural asset. As a matter of fact, the conscious integration between traditional (2D) and innovative (mostly 3D) methods and tools can effectively ensure quality, efficiency, and sustainability in heritage conservation. [CM]

### 1.2 Digital representation for Architectural Heritage conservation

In recent years, digital tools already widespread in the AEC sector have been addressed to support the conservation of AH. Depending on the level of information required, different data capturing and processing frameworks are available to provide the most appropriate representation of the AH consistency. (Letellier and Eppich, 2015; Patias and Santana, 2011) outline three main levels of documentation: reconnaissance, preliminary, and detailed. At the reconnaissance level (DL1), photographic reports, initial condition assessments, and descriptive sketches are employed to generate a representation of a site that is not drawn to scale. This type of documentation does not provide measurements of geometry, making it unsuitable for quantitative analysis of the building's consistency. Among other more traditional documents, spherical panoramas are increasingly used at this step, providing 360 degrees representations of an AH for identifying damages and underlying causes, such as faults on the floor or the ceilings (Fangi, 2011; Napolitano et al., 2017).

Concerning the preliminary documentation (DL2), it refers to representations such as plan and elevation drawings with an accuracy of approximately ±10 cm. Additionally, structural elements are represented with an accuracy of approximately ±2 cm. This level of documentation yields straightforward geometries that are appropriate for computational modelling. However, it is important to acknowledge that various practical issues must be considered and addressed within the project's scope when implementing this level of recording. Simplified geometries, commonly used in documentation, may overlook the inherent characteristics of existing structures where elements are rarely perfectly straight, square, or horizontal. Finally, detailed documentation (DL3) takes advantage of different tools to generate a representation that includes plan and elevation drawings with an accuracy of approximately ±1 cm. It also captures detailed structural elements with an accuracy of approximately ±2 mm, enabling precise documentation of the building's geometry and consistency. Nowadays, the 3D survey is widely used to generate accurate models, which provide metric information required for DL2 and DL3. However, it is important to note that this process can be resource-intensive in terms of time, funding, and data management. Therefore, it is advisable to employ it only when it aligns with the project's scope and resources. The advantage of spherical panoramas lies in their efficiency in capturing and processing phases, requiring a few seconds to be generated. Moreover, combining Virtual Tours (VT) and Information Modelling (IM) it is possible to create cost-effective solutions for projects that need to depict 3D conservation challenges, but do not have the budget or time for a full 3D model (Napolitano et al., 2018)

If quantitative analysis is required, both photogrammetry and laser scanning can generate point clouds that provide accurate metric information. (Park et al., 2020) introduce the concept of Point Cloud Information Modelling (PCIM), which is a point cloud with an object-oriented hierarchical structure that records information related to building elements. Starting from a point cloud of a building, a PCIM is obtained by segmenting it according to its architectural elements and then associating different semantic information to the obtained point groups. Potree Viewer is an effective solution for visualizing and exploring point clouds. It is a web-based renderer that allows users to explore data sets with billions of points (Schütz, 2016). One of the primary benefits of visualizing point clouds through a web browser is the ability to share information among stakeholders without requiring the installation of third-party applications or the transfer of large amounts of data beforehand. Additionally, the variety of measuring tools allows users to analyze and measure building geometry using Potree, without the need for time-consuming 3D modeling (Yeshwanth Kumar et al., 2019).

A point cloud obtained through photogrammetry and laser scanning can only record and enable analysis of the current state of a building. However, it can also provide a geometric reference in scan-to-BIM workflows via NURBS (Non-Uniform Rational Basis-Splines) (Diara and Rinaudo, 2019). HBIM has been demonstrated to be the most appropriate methodology for supporting long-term conservation strategies and managing future interventions (López et al., 2018). In (Acierno et al., 2017; Di Stefano et al., 2020) a successful approach for modeling architectural knowledge is presented to actively enhance the preservation of built heritage. This involves promoting collaboration among stakeholders and ensuring seamless interoperability between datasets. Moreover, the conservation of an AH requires a comprehensive understanding of its historical and contextual knowledge. This implies that possessing a diachronic awareness of a building's history is crucial for the preservation processes of heritage assets. HBIM is also effective to this end; indeed, it allows to record historical information, providing significant advantages to the management, periodic monitoring operations, and enhancement processes (Beltramo et al., 2019). In addition to the temporal sequence of transformations, which represents the essence of their evolving nature, AH is also characterized by construction techniques and materials affected by decay processes that differ significantly from those found in contemporary buildings. In alignment with this perspective, (Santoni et al., 2021) introduce a novel BIM workflow aimed at establishing criteria that consider both the temporal sequence and the distinctive construction features of historical buildings. (Mammoli et al., 2021; Oreni et al., 2014) focus on the application of an HBIM approach to model the temporal dimension of historical and archaeological architectures, with a particular emphasis on stratigraphic analysis. The study adopts a methodology tailored for practitioners, with the aim to generate informative models that highlight the various phases in a building's history.

The effectiveness of the HBIM method, as demonstrated in the above-mentioned studies, is hindered by the long processing times required for AH 3D modelling, which needs a level of detail adequate to represent unique features (Valentini et al., 2023). To date, various workflows have been examined and crafted (Allegra et al., 2020; Quattrini et al., 2015), primarily utilizing software intended for the parametric modelling of new structures. However, these approaches often lead to manual and time-intensive scan-to-BIM processes. In (Pepe et al., 2021), the HBIM workflow is instead carried out through an innovative procedure based on tools provided by non-parametric 3D modeling software, aimed at implementation in a GIS environment. (Angeloni et al., 2023) present a workflow based on the use of a non-parametric automatic 3D modeling software and an open-source Industry Foundation Classes (IFC) authoring platform to combine accurate geometry and semantic information. So, there are several ways to generate detailed models, based on metric data from massive point clouds and enriched with semantic information. However, there is still no widely applied workflow that automates the scan-to-BIM process, and the automatic generation of HBIM from point clouds. [RA; JM]

## 2. RESEARCH AIM AND CASE STUDY

### 2.1 A three-step methodology for representing and conserving heritage

Based on these premises, the paper describes and discusses a workflow for the integrated representation of architectural heritage. This workflow uses 2D and 3D digital tools for preventive and planned conservation, supporting the different stages of the whole process.

The aim is to work with digital technologies and environments that complement each other and facilitate the interactive exploration of the asset and its context, allowing the inspection of its architectural elements, stratigraphic layers, materials, degradation phenomena and previous restorations. This also includes the control of geometric aspects such as measurements, the management of heterogeneous cultural contents and the planning of future interventions, providing opportunities for sharing and comparison between different stakeholders.

To achieve this goal, a three-step methodology has been developed involving the implementation of a Virtual Tour Information Model (VTIM), a Point Cloud Information Model (PCIM) and a Historic Building Information Model (HBIM), all of which have been experimented and tested on the former church of San Francesco in Fano, Italy (Fig. 1). [CM]

### 2.2 Heritage in transition: the church of San Francesco (Fano, Italy)

The former church of San Francesco is located in the historic centre of Fano, in the province of Pesaro-Urbino, Italy. The building is currently closed to the public, but it doesn’t go unnoticed by passers-by who catch a glimpse of its unique spatiality beyond the gates. The church stands as an urban void, having been roofless for almost a century; it is surrounded by neoclassical ornate walls that offer no protection from the elements, and the grass grows wildly on the ancient pavement.

The constructive and transformative evolution of the church is truly complex and still unfolding. Built-in the 13th century by the mendicant Franciscan order as a resting place for pilgrim monks, next to the adjacent convent, the church had a simple architecture with a single nave, a roof with wooden trusses, and three rectangular apsidal chapels covered with cross vaults. Between the 14th and 17th centuries, the building was chosen by the Malatesta family as a sepulchral chapel and underwent modifications, including the addition of a portico in front. In the 18th century, the convent underwent renovations and a century later, the church was completely redesigned. It was raised by around 9 meters, the rectangular apsidal chapels were replaced by semicircular ones, the nave was covered with a barrel vault and the presbytery with a dome, and finally, the medieval interiors were updated with neoclassical decorations (Angeloni et al., 1993; Galli, 2011).

From 1860 onwards, several factors posed threats to the preservation of the asset. Firstly, the suppression of religious orders and structural issues resulting from 19th-century transformations led to the abandonment of the church. Subsequently, the 1930 earthquake damaged the roof to such an extent that it was partially destroyed and later dismantled for public safety reasons. There were discussions regarding the preservation of the church, with proposals also made for its complete demolition. The debate involved influential figures in Italian restoration culture who defended the need for conservation, including Gustavo Giovannoni, Ferdinando Forlati, and, more recently, Giovanni Carbonara, who contributed to the most recent conservation project, which was only partially completed between 2001 and 2009 (Galli, 2013; Cuppini, 2004).

Since then, the church of San Francesco has been in a state of standstill, unused and open to the public only on rare occasions. Conflicting views on the objectives and outcomes of restoration efforts, coupled with limited funding, have resulted in only temporary and non-definitive safety measures, such as propping and demolition of endangered parts. A strategic, medium- to long-term preventive and planned conservation program has never focused on the reversal of the internal-external relationship, the naturalization process, the challenge of exposure to weathering, and the potential for new use and enjoyment.

The challenge today is to manage this heritage in transition while enhancing the established image of the open-air church and planning for continuous care from a predictive perspective of risks. To achieve a comprehensive understanding and efficient management of heterogeneous data, a well-structured process is required that includes the acquisition, integrated representation, planning, and management of information (Moioli 2023).

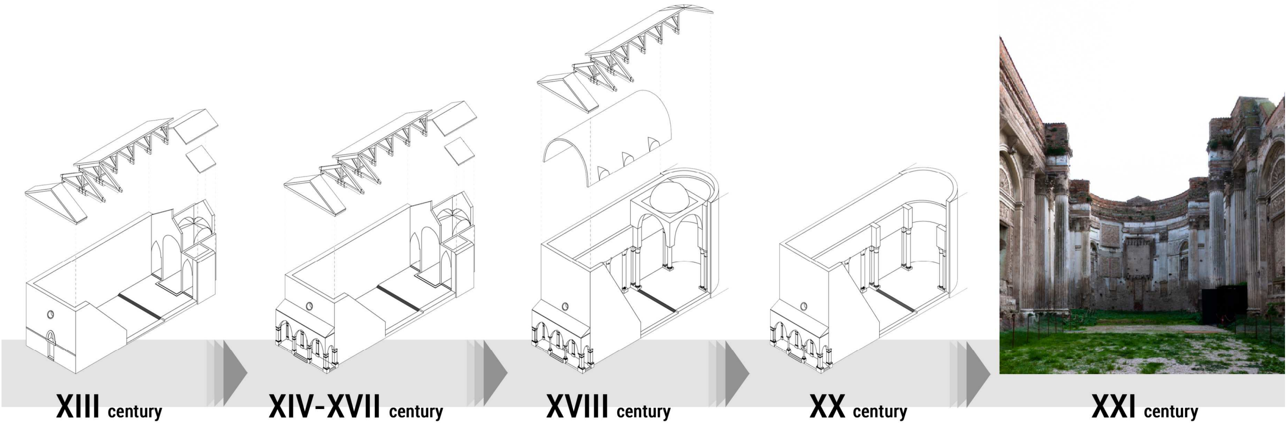

**Figure 1.** The Church of San Francesco, Fano (Italy). Brief overview of the main phases of the building's development (G. Di Giacinti).

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Starting from these assumptions, the church in Fano serves as an emblematic pilot case for implementing and validating this workflow (Fig. 2). [CM]

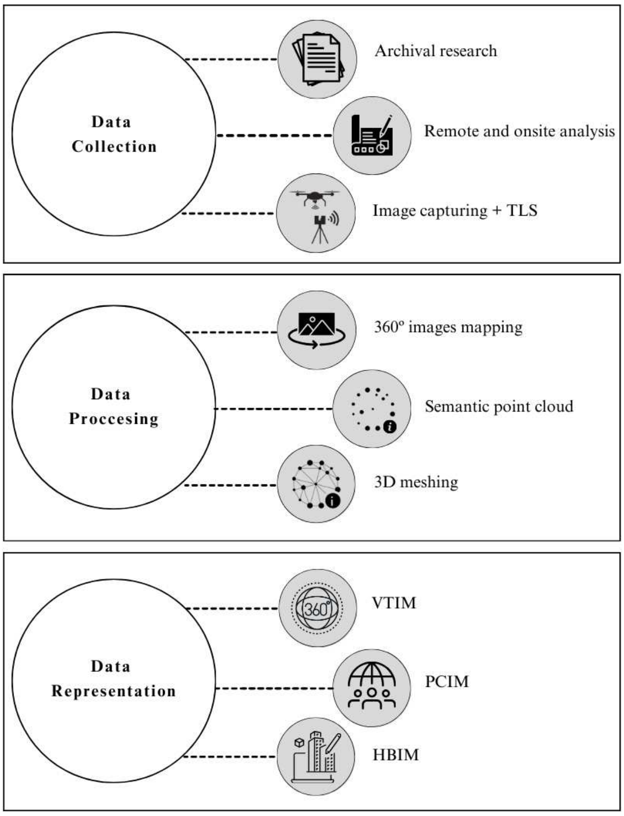


**Figure 2**. Established workflow for digital representation of architectural heritage.

## 3. MATERIAL AND METHODS

### 3.1 VTIM for reconnaissance documentation level

To meet the requirements of the reconnaissance level, a VTIM was generated as the primary stage of documentation. Firstly, panoramic images of the exteriors and each bay of the interiors were obtained by stitching together sets of images acquired using a Nikon D90 camera with an 8mm f/3.5 fisheye lens. The camera was mounted on a tripod equipped with a NodalNinja 3 panoramic head to fix its rotation around the nodal point. A traditional camera mounted on a panoramic head has been preferred to a 360° camera to provide a higher level of detail and chromatic fidelity. Considering the distance from the camera of the furthest element portrayed, the Ground Sample Distance (GSD) is 5 mm, which was considered proper to detect decay and damage phenomena. The different sets of images were separately stitched using PTGui, then imported into Pano2VR a virtual tour software that converts panoramic images into interactive experiences. Moreover, this software enables the manipulation of the uploaded images in Adobe Photoshop, so, by creating different patches, each panorama was annotated with different semantic information, particularly: building components, material, decay and damage phenomena, historical phases, and former structural interventions. By changing patch visibility, it is possible to visualize the required information on the panorama.

The VTIM interface was designed for ease of use. By clicking on the hotspots distributed in the panorama, the user can move to the next one or go back to the previous one. Moreover, a map can be used to move to a specific location. The command bar allows the user to select the different semantic information to be displayed, and to access bibliographical and archival databases. It allows to overlay of archival images generating a sort of augmented virtuality experience, too. In addition, a user with an admin account can generate a report by clicking on each component noting information after a site visit, otherwise, reports and other datasheets can only be accessed and consulted if they have been previously filled in. (Fig. 3). [RA]

**Figure 3.** VTIM. Top to bottom, decay analysis representation, and archival image overlay.

### 3.2 Point Cloud to PCIM: integrating geometric accuracy and semantic information

A PCIM was identified as the second step in the documentation of the former church of San Francesco. A point cloud is a set of data points in a three-dimensional coordinate system, so it can also represent a building and provide the geometric information required for preliminary and detailed documentation levels.

Terrestrial Laser Scanning (TLS) and photogrammetry were integrated to ensure geometric and colorimetric accuracy. Moreover, the whole 3D survey was carefully planned to obtain uniform lighting and avoid sharp shadows. The data acquisition lasted one day, and it involved two operators.

First, black and white targets were placed on the ground to define the reference system, which was then surveyed using a GPS HiPER HR with RTK (Real Time Kinematic) method. A TLS Leica Geosystem P40 ScanStation was then used to scan from the ground the exterior and interior of the building. Set to a scan density of 6.3 mm at 10 m, a total amount of 35 scans were required to document the whole building. In addition, from each scan station, 8 images were captured via a Nikon D90 digital camera mounted on a NodalNinja 3 panoramic head, as performed for the VTIM. Lastly, an Unmanned Aerial Vehicle (UAV) photogrammetric survey was performed using a DJI Mavic 2 PRO. This UAV system is equipped with a 1-inch CMOS sensor with an effective pixel count of 20MP. A sequence of 224 images representing the upper parts of the building was acquired while flying at an altitude of 15 m above ground level.

Once the survey campaign was over, using the software Leica Cyclone Core, each TLS point cloud was coloured with the RGB values of the 360° panoramic image obtained by stitching the images captured from the corresponding scan station. Then, all the TLS point clouds were aligned into one representing both the interior and exterior. Meanwhile, images captured by UAV were processed in Agisoft Metashape according to the SfM-DMVR method. So, another RGB-coloured point cloud representing the upper part of the building was obtained. Finally, the coordinates of black and white targets were used to refer both TLS and SfM-DMVR point clouds to the WGS84 coordinate system and, therefore, to merge them. As a result, each point has its set of Cartesian coordinates referred to the WGS84 coordinate system, RGB and normal values, and the ones from TLS intensity values too. However, more scalar fields referred to other information can be recorded. By leveraging this possibility, all semantic information already annotated in the panoramic images was transferred to the point cloud by following the procedure outlined below. The VTIM panoramic images were imported into Agisoft Metashape to be aligned and referred to the WGS84 reference system by placing markers. Then, the point cloud was imported in the same file, by changing the set of VTIM panoramic images from the ones with RGB values to the semantic annotated, the point cloud was coloured according to each information layer. Therefore, five different point clouds with RGB values related to semantic information were exported. Finally, the open-source software Cloud Compare was used to record a Scalar Field (SF) on the original point cloud for each information layer, based on the RGB values of each semantic-colored point cloud (Fig. 4). The PCIM was then processed to be virtually explored in the Potree Viewer. The interface was edited to allow access to bibliographical and archival databases, as well as state of conservation reports filled within the VTIM. [RA]

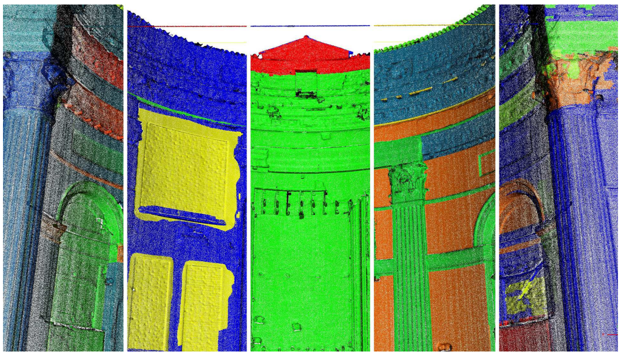


**Figure 4.** From left to right, point cloud classified according to building components, historical phases, former structural interventions, materials, decay and damage phenomena.

### 3.3 From 3D mesh segmentation to HBIM: a framework for future interventions

The final stage of this AH representation workflow consisted in an HBIM project, with a specific focus on the apse of the church.

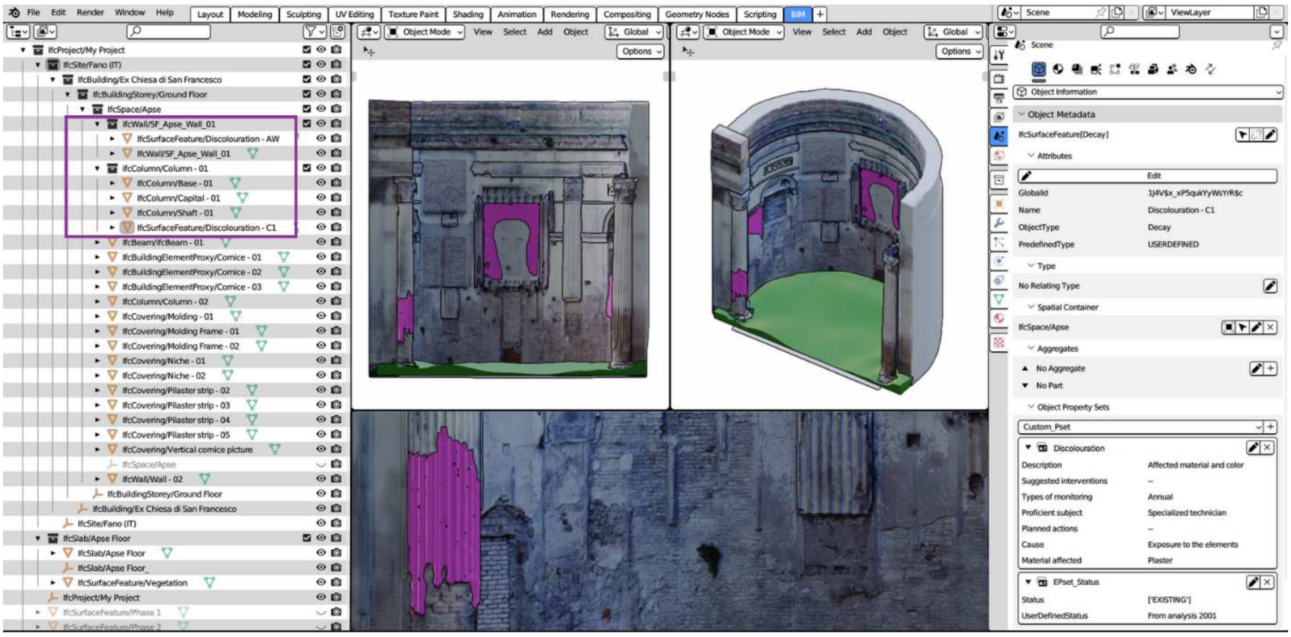
Firstly, a 3D mesh was automatically generated, and all the SFs associated to the PCIM were transferred to its vertices. Then, the 3D mesh was automatically segmented according to the building components information. Before importing meshes in the BIM environment, additional steps were required, including mesh editing to remove topological errors and texturing, using panoramic and UAV images. Furthermore, to handle unusual shapes, B-Rep modeling was employed as a valuable approach.

The 3D surfaces related to the different building components were saved in OBJ format preserving textures. Thanks to this, it was possible to present material analysis both with textures and associated metadata. Moreover, two copies of each building component 3D mesh were respectively segmented according to the historical phases and the decay analysis SFs, then exported in PLY format to keep vertex color values. To set up an HBIM project, all of them were imported into the open-source software Blender using the BlenderBIM add-on. The area of the apse was represented as an *ifcSpatialElement* entity with the *ifcSpace* classification. Within this entity, all the building components of the apse were stored as *ifcElements*. This allowed for the development of the IFC 4 Schema, ensuring compatibility with the relations and properties of the AH. In addition to this, a significant number of *ifcPropertysets* was generated. These sets of properties, stored as datasheets within BlenderBIM, contain information on materials, decay and damage phenomena, or historical phases of each *ifcElement*. Alternatively, if the data relates to the entire building or general properties, it was associated to the *ifcBuilding* entity.

Due to the use of surfaces in the BlenderBIM project, a comprehensive analysis was conducted on the whole list of *ifcClass* to identify the most suitable for the 3D meshes segmented according to decay and damage phenomena of each building component. Finally, these 3D surfaces were assigned to the *ifcSurfaceFeatures* class and associated to a set of properties related to material and decay analysis, and aspects related to future interventions. Then, each one was linked to the related *ifcElement* through an aggregate tool which affords the collection of separate elements presenting some kind of relationship (Fig. 5). The materials documented in this work were also stored in separate property sets thanks to the latest BlenderBIM update which added this new functionality. According to the project library, was the predefined one of lack of a heritage common library for this parametric element. Extra documentation, such as previous plans, historical photos, and references, was added using *ifcDocuments*. The most interesting point is the possibility of adding different documents for each element when it is strictly related to an element. This consideration means that all the documentation added to the VTIM is linked now to the HBIM project. This application allowed a valuable representation of the heritage features, including specific details at the element level and broader data at the building level. Additionally, it facilitated the integration of previously collected data into this final comprehensive representation without any loss of information. [JM]

## 4. RESULTS AND DISCUSSION

The first digital representation of the former church of San Francesco is an interactive VTIM available online on PCs, tablets, smartphones, and VR headsets, too. Thanks to panoramic images, users explore the building areas selecting among different pre-set points of view. The VTIM provides an adequate overview of the architectural components, which is useful for the qualitative assessment of its state of conservation. Furthermore, the user can easily switch between different thematic information, such as materials, decay and damage phenomena, historical phases, and former structural interventions, which overlay the panoramic image according to color legends, thus making it easy to understand relations with building components.



- IfcProject/My Project
  - IfcSite/Fano (IT)
    - IfcBuilding/Ex Chiesa di San Francesco
      - IfcBuildingStorey/Ground Floor
        - IfcSpace/Apse
          - IfcWall/SF_Apse_Wall_01
            - IfcSurfaceFeature/Discolouration - AW
            - IfcWall/SF_Apse_Wall_01
          - IfcColumn/Column - 01
            - IfcColumn/Base - 01
            - IfcColumn/Capital - 01
            - IfcColumn/Shaft - 01
            - IfcSurfaceFeature/Discolouration - C1
          - IfcBeam/IfcBeam - 01
          - IfcBuildingElementProxy/Cornice - 01
          - IfcBuildingElementProxy/Cornice - 02
          - IfcBuildingElementProxy/Cornice - 03
          - IfcColumn/Column - 02
          - IfcCovering/Molding - 01
          - IfcCovering/Molding Frame - 01
          - IfcCovering/Molding Frame - 02
          - IfcCovering/Niche - 01
          - IfcCovering/Niche - 02
          - IfcCovering/Pilaster strip - 02
          - IfcCovering/Pilaster strip - 03
          - IfcCovering/Pilaster strip - 04
          - IfcCovering/Pilaster strip - 05
          - IfcCovering/Vertical cornice picture
          - IfcSpace/Apse
          - IfcWall/Wall - 02
        - IfcBuildingStorey/Ground Floor
      - IfcBuilding/Ex Chiesa di San Francesco
    - IfcSite/Fano (IT)
  - IfcSlab/Apse Floor
    - IfcSlab/Apse Floor
    - IfcSlab/Apse Floor_
    - IfcSurfaceFeature/Vegetation
  - IfcProject/My Project
  - IfcSurfaceFeature/Phase 1
  - IfcSurfaceFeature/Phase 2

Object Metadata
IfcSurfaceFeature[Decay]
Attributes
Edit

| | |
|---|---|
| GlobalId | 1J4V$x_xP5qukYyWsYrR$c |
| Name | Discolouration - C1 |
| ObjectType | Decay |
| PredefinedType | USERDEFINED |

Type
No Relating Type
Spatial Container
IfcSpace/Apse
Aggregates
No Aggregate
No Part
Object Property Sets
Custom_Pset

Discolouration

| | |
|---|---|
| Description | Affected material and color |
| Suggested interventions | – |
| Types of monitoring | Annual |
| Proficient subject | Specialized technician |
| Planned actions | – |
| Cause | Exposure to the elements |
| Material affected | Plaster |

EPset_Status

| | |
|---|---|
| Status | ['EXISTING'] |
| UserDefinedStatus | From analysis 2001 |

**Figure 5.** BlenderBIM environment. On the left, the developed IFC hierarchy, with decay analysis associated to each architectural element. In the center, 3D views of the apse, with discoloration decay highlighted in pink. On the right, *ifcPropertySets* of decay analysis.

Moreover, a PDF viewer was embedded within the VTIM to display the building data sheet (a sort of ID card of the heritage site), the critical issues abacus, and the 2D representations of previous restoration works. In addition, external link buttons allow users to access bibliographical and archival web databases, containing documentation collected through extended research in libraries and archives. This approach is based on the widely used BIM methodology, which aims to create models capable of storing and managing the intrinsic information of a complex object, functioning as a true "data collector". By using spherical panoramas instead of 3D models, a VTIM can be a faster tool for sharing information between conservators and building managers. For example, if a building manager has created a VTIM environment of an AH with decay symptoms due to an unidentified problem, a conservator can remotely explore the building, access several information, and, finally, make a diagnosis or suggest further instrumental analysis. VTIM provides a 360° representation of the building, allowing for on-site inspection of all damages, even in hard-to-reach areas; additionally, specific areas can be zoomed in for higher detail. Moreover, by clicking on a specific building element, it is possible to fill in the related inspection sheet and report (Fig. 6).

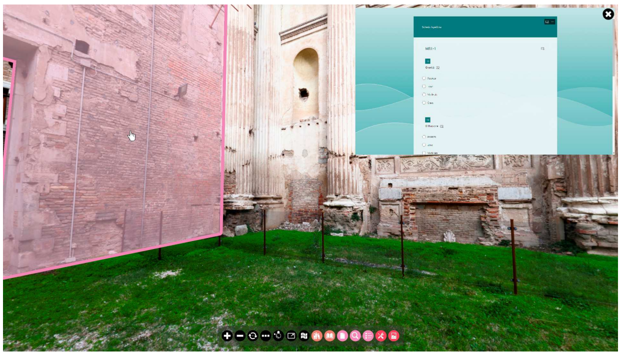


**Figure 6.** By selecting a building component within the VTIM, it is possible to generate a corresponding inspection sheet.

The VTIM lacks in geometry information; therefore, the PCIM represents a further step in the representation process of the building. It implements also metric information, which is essential for performing quantitative analysis. A PCIM based on photogrammetry and laser scanning can achieve an accuracy of ±2 mm, making it suitable for detailed documentation. Concerning the presented case study, the PCIM in a LAS format was imported into the Potree Converter to be shared online using the Potree Viewer. The UI of this viewer was tailored to include color legends regarding the different information layers of the PCIM. Also, links to bibliographical and archival databases, already available within the VTIM, were added to the Potree Viewer UI (Fig. 7).

Fasi storiche
- 🟩 Ricostruzione XIX secolo (1850)
- 🟧 Interventi XX secolo
- 🟥 Restauro XXI secolo (2001-2007)
- 🟪 Non classificato

Nella sezione "Scene" seleziona la nuvola di punti "San Francesco" e attiva l'attributo Fasi_storiche.

**Figure 7.** PCIM in Potree Viewer coloured according to the historical phases.

Moreover, it was added another link to an external database containing the building data sheet, the abacus of its critical issues, 2D drawings, and inspection sheets and reports related to each building component. However, the key benefit of the PCIM compared to VTIM remains the measurement of distances and areas. Furthermore, thanks to the Potree Viewer features, single points, sections, and regions of the PCIM can be exported as .dxf and .las files, respectively.

Lastly, the highest representation level for AH introduced in this paper is an HBIM. The PCIM represents the current state of the building, providing both semantic and 3D information. The

HBIM represents a further step, including 4D – time planning, 5D – cost analysis, 6D – asset operational management, and 7D – sustainability. Moreover, an HBIM project can be adapted to the specifics of a building and based on the manager's requirements. Focusing on the result obtained for the former church of San Francesco, the documentation already shared within the VTIM and PCIM was integrated thanks to *ifcDocument* and *ifcLinks*, which means that changes made in the external databases are updated automatically in all the different digital representations presented. This approach allows different team members to access the most updated documentation, promoting an efficient collaboration according to the Common Data Environment (CDE): work in progress (WIP), Shared (S), Published (P), and Archived (ARC).

According to the Italian technical legislation UNI 11337, many of the IFC elements integrated into the HBIM project presented in this paper reached a LOD D-E (digital twin). This standard corresponds to the international LOD 5, the UK reference system. As geometries were automatically generated from an accurate point cloud, the HBIM results in a high level of geometry (LOG), that matches the same LOI (Level of Information) provided by the building analyses and documentary research. [RA; JM]

## 5. CONCLUSIONS

The process of AH knowledge and investigation should be indented as an information flow structured on different level of analysis, meeting conservation requirements at each stage. Seamless transfer data from one level of documentation to another improves the sustainability of the conservation process, facilitating a diachronic awareness of a building history.

The presented methodology achieved this goal exploiting the potential of three digital representations which are distinct but closely integrated: VTIM, PCIM, and HBIM. These representations provided varying levels of documentation, with data from the lower levels forming the basis for the higher ones, following a circular data reuse logic that optimized the entire process in terms of time and costs. All representations were enriched with semantic information, allowing the inspection of its architectural elements, stratigraphic layers, materials, degradation phenomena and previous restoration works. Moreover, the PCIM enabled the control of geometric aspects such as measurements, whereas the HBIM facilitated the planning for future interventions, providing opportunities for sharing and comparison among stakeholders. All the digital representations presented an effective solution to contain and manage the information of a complex heritage site, such as the former church of San Francesco in Fano, functioning as a data collector.

Critical investigations are crucial to support the conservation and management process, offering a comprehensive understanding of the heritage conditions. The use of panoramic images has proven to be effective for semantic annotation, making it accessible even to professionals without expertise in 3D modelling. Nevertheless, while images contributed to qualitative information recording, the point cloud generated from laser scanning and photogrammetry data played a pivotal role in delivering geometric and quantitative information. Focusing on the highest level of documentation, the HBIM workflow presented in this paper overcomes issues highlighted in other studies, which used BIM software designed for new constructions. The proposed methodology does not envisage the parametric modelling of building geometries, starting from the assessment that AH consists of a complex and often layered architecture that is difficult to reduce to simple geometric rules. The building elements are represented as 3D meshes automatically generated from the point cloud obtained by merging data from photogrammetric and TLS surveys. This solution provided both a higher geometric accuracy and a less time-consuming 3D modelling process. Since the HBIM project uses the IFC standard it can be hosted and shared using Cloud Based Platform. In this regard, it must be also emphasized that the IFC classes have proven to be effective in setting up the relationship between geometry and semantic information, thanks to element association dependencies and custom property sets.

In conclusion, the paper highlights the importance of aligning objectives and tools in heritage knowledge, preservation and management processes. The presented three-step methodology addresses this issue, and fully incorporates both traditional and innovative methods and tools to enhance the quality and efficiency in heritage conservation. It also underlines the potential of digital technologies in building a heritage knowledge infrastructure, which is a prerequisite for long-term and predictive conservation strategies. [PC; CM; RA]

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