

Article

A Federated HBIM Workflow for Complex Heritage Conservation: Data Integration, Automation, and Construction-Phase Support for the Floor of the Holy Sepulchre Basilica

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Abstract

The management of complex heritage conservation projects requires the integration of heterogeneous datasets, multidisciplinary expertise, and information generated throughout investigation, design, construction, and maintenance activities. Although Heritage Building Information Modelling (HBIM) is increasingly adopted as a framework for organising heritage information, its implementation in complex conservation projects remains challenging due to the coexistence of multiple disciplines, modelling granularities, and information requirements. This paper presents the development of a federated HBIM system for the conservation of the floor of the Basilica of the Holy Sepulchre in Jerusalem and, starting from this real multidisciplinary implementation, derives a generalised methodological workflow for similar heritage conservation projects. The proposed workflow consists of four main phases: (i) definition of project objectives and information requirements, (ii) acquisition and organisation of multi-source datasets, (iii) development of a federated HBIM architecture integrating modelling, information management, and automation, and (iv) operational use of the federated model throughout the conservation process. A key aspect of the proposed approach is the organisation of federated sub-models according to both disciplinary responsibilities and specific operational purposes, allowing different geometric and semantic granularities to coexist within a coordinated information environment. The study also demonstrates the enabling role of automation in supporting the management of highly granular datasets and repetitive information management tasks. The application to the Holy Sepulchre Basilica demonstrates the applicability of the proposed workflow in a real multidisciplinary conservation project, while the abstraction process provides a transferable methodological framework for similar heritage conservation contexts.



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Keywords: HBIM; federated models; cultural heritage conservation; information management; scan-to-HBIM; Visual Programming Language (VPL); workflow automation; digital twin

1. Introduction

The conservation of complex monumental contexts of historical importance requires approaches that go beyond mere geometric documentation. When an asset has great historical, cultural, and artistic value, multiple layers of construction and materials, ongoing usage constraints, heterogeneous diagnostic investigations, and a plurality of actors with different

roles and responsibilities, the main challenge becomes the coordinated management of knowledge and its transformation into traceable operational choices. In such scenarios, data are produced by different disciplines, at different scales, and in formats that are often not immediately interoperable. Without a unifying framework and strategy, information tends to remain fragmented between reports, tables, survey datasets and specialist deliverables, with a loss of effectiveness in the design, construction and post-intervention management phases.

In this context, Heritage Building Information Modelling (HBIM) is increasingly perceived as an information system capable of connecting geometry, semantic content and external documentation. Furthermore, the knowledge of the building acquired during the study and design phases, as well as during the construction phases, can be stored, queried and progressively enriched over time. However, the operational implementation of HBIM in highly complex contexts still raises open questions. How can granularity, multi-scale, and multi-disciplinary representation be defined in relation to conservation needs? And how can modelling be made sustainable when the number of objects and attributes grows to the point where manual procedures become impractical, with consequent risks of inconsistency and errors? These challenges require methodological approaches capable of structuring heterogeneous information while supporting multidisciplinary collaboration throughout the conservation process.

This paper presents the development of a federated HBIM system for the conservation project of the floor of the Basilica of the Holy Sepulchre in Jerusalem. The project required the integration of multi-source surveys, diagnostic investigations, and heterogeneous documentation produced by multiple stakeholders within a common information environment, while supporting the operational needs of the conservation process. Starting from this real multidisciplinary implementation, the organisational and technical decisions adopted during the project were subsequently analysed and abstracted into a general methodological workflow. The resulting framework identifies the key steps required for the development of federated HBIM systems in similarly complex conservation projects, while deliberately remaining independent of specific software environments or national BIM regulatory frameworks.

The proposed workflow is based on the assumption that a single HBIM model rarely satisfies the heterogeneous information requirements of complex heritage conservation projects. Instead, the framework adopts a federated architecture in which coordinated sub-models are organised according to their intended purpose, required level of detail, and information content. Unlike many federated BIM implementations, the proposed approach defines sub-models not only according to disciplinary responsibilities but also according to specific operational objectives, allowing multiple representations of the same asset to coexist at different geometric and semantic granularities. Within this framework, automation is considered an enabling component for managing highly granular datasets and supporting their systematic integration into the federated information environment.

The remainder of the paper is organised as follows. Section 2 reviews the state of the art on HBIM, federated modelling, and automation in heritage conservation. Section 3 presents the implementation of the federated HBIM system through the conservation project of the floor of the Basilica of the Holy Sepulchre. Section 4 abstracts the experience gained from the case study into a generalised four-step methodological workflow. Section 5 discusses the scientific implications, implementation choices, limitations, and future developments of the proposed framework, while Section 6 presents the conclusions.

2. Related Works on HBIM, Federated Models and Automation Workflows in Complex Heritage Sites

The conservation project of the floor of the Holy Sepulchre Basilica confronted the authors with a combination of challenges that are often addressed separately in the HBIM literature: the management of a highly complex heritage site, the integration of heterogeneous multidisciplinary data, the coordination of multiple stakeholders, the need for federated models, and the automation of highly granular modelling and information-management tasks. For this reason, the following literature review is organised according to the same logical sequence that emerged during the development of the project itself. Rather than discussing these topics as independent research areas, the review retraces the conceptual path that led to the definition of the proposed workflow. This practice-driven process subsequently allowed the methodological approach developed for the Holy Sepulchre Basilica to be abstracted and generalised into a structured and replicable framework that can support other heritage conservation projects characterised by a comparable level of complexity.

2.1. Conservation of Complex Sites and the Role of HBIM as an Information System

The complexity that characterises monumental sites of great historical, artistic, cultural, and religious significance manifests itself on several levels. Generally, from a physical point of view, these structures have irregular geometries, several superimposed layers of construction, and a considerable heterogeneity of materials, which make it difficult to represent them in a unified and coherent manner. Added to this complexity is the managerial complexity linked to the presence of multiple interested parties within the intervention activities (e.g., religious authorities, visitors, external funding bodies, restorers, architects, engineers, archaeologists, and conservation specialists), each with different needs, procedures, and perspectives. There is also functional complexity, due to the fact that these buildings often have to remain operational, defining particularly restrictive conditions for construction site operations and therefore requiring more careful and targeted design. Specifically, in the case study presented in this article, these operating conditions refer to the religious community's need to carry out religious ceremonies without interruption and allow the regular flow of worshippers. However, thinking more generally, it is possible to imagine the need to maintain a constant flow of people who need to carry out activities or a flow of people visiting the complex. Finally, there is a documentary complexity arising from the necessary integration of heterogeneous sources, which are often not harmonised and/or harmonizable with each other (e.g., historical documentation, existing or newly acquired digital surveys, diagnostic investigations, monitoring activities, and, in general, materials produced by different disciplines) that must be brought together into a unified and queryable information system. This approach is well represented by BIM methodology, and in fact it is not uncommon to find literature discussing HBIM solutions designed to manage and support maintenance, conservation and construction activities at such complex architectural sites [1–3]. A typical starting point in those scenarios is a geometric survey performed by implementing various geomatics techniques, following a so-called scan-to-BIM approach [4,5].

Recently published literature reviews indicate that although geometric modelling remains a challenging task, particularly due to the lack of standardisation and regularity of the elements to be modelled, crucial points are the information content, its management, and the actual use of the model in the building lifecycle [6]. This would make the model the ideal place to store all the information that has been studied, researched and used to define the project (before) and that could later be useful in the construction and management phases (after). Proof of this is the fact that, in the case of research related to planned

conservation, there is often a desire for a “return to the building” [6], i.e., the use and sharing of the data collected, including through desktop or web-based platforms, which are intended to enable model use directly on site, even by non-expert users. More specifically, the model developed for the conservation/design phase of restoration work could then support Facility Management (FM) activities, which is not always straightforward [7], especially with HBIM and for various reasons. The reasons are linked to poor integration between FM and BIM processes resulting in significant data loss, sometimes insufficient engagement of Cultural Heritage stakeholders (even in terms of their knowledge of BIM processes and information management), and perhaps even insufficient legislation on the matter. For this reason, HBIM models are often created differently depending on the type of use [7], and a model used solely for conservation activities will tend to have a higher level of geometric accuracy, with less associated information, while one created specifically for FM will have lower geometric accuracy but a greater amount of associated information, with a different granularity (i.e., total number of identifiable objects).

Furthermore, both in FM logic and when considering conservation interventions that require the contribution of different disciplines, interoperability becomes crucial. Interoperability can be understood as the ability of the HBIM model to support and exchange data with other systems and is generally used to perform analyses and simulations (e.g., structural, energy) [8,9]. Interoperability can be achieved in several ways. The main route is the use of open formats, above all Industry Foundation Classes (IFC), which enable the exchange of geometric and non-geometric data. However, IFC is not always effective, especially for historic buildings whose components cannot be fully described by existing IFC entities, requiring other approaches. In those cases, interoperability is pursued through geometry-only transfers, simplified representations, custom intermediate models, self-developed tools, and formats tailored to specific analytical domains [6].

Another relevant approach to information management, which incorporates multiple interdisciplinary contributions to the management of the architectural complex, is the use of federated models. This method is established in BIM standards [10], where separate discipline models such as architectural, structural, and MEP (Mechanical, Electrical and Plumbing) are combined through a federation strategy. As an example, [11] shows that BIM research emphasizes the integration of separate models and systems within construction networks to support coordinated multi-party work.

2.2. HBIM Federated Models for Complex Heritage Contexts

Complex architectural scenarios require an interdisciplinary approach, which not only brings together professionals with different expertise to tackle conservation, but also involves the implementation of various interventions carried out from different perspectives and with varied input and output data. In this case, the ideal solution, which is in fact the one proposed by the standards for BIM implementation, is to create several sub-models, one for each discipline, which coexist and make up a single federated model.

The federation strategy seems not yet to be widely adopted in heritage contexts. In fact, while many studies about HBIM assume that a single model can satisfy all stakeholders [7], there are only a few studies that propose separating the model into sub-models (that together form a federated system) with different purposes, like geometric accuracy, semantic meaning, and information attached. Moreover, it is interesting to note how the various sub-models are not directly related to different disciplines, but are used to better describe different aspects within the same discipline.

For example, the authors of [12] theorise that a single HBIM cannot satisfy every requirement and that different representations of the same building may need to coexist. They distinguish between a survey-driven “black-box” model, a design-intent “white-box”

model, and a hybrid “grey-box” model. Used together, these models form a composite representation in which each contributes to specific, complementary information. The survey model captures the current physical state, the design-intent model reconstructs the construction logic, and the hybrid model integrates both. Their approach treats the HBIM not as a single, fixed model but as a coordinated set of models, each offering a distinct view that supports different analytical or documentation needs.

A similar logic, in which the same object is modelled in multiple ways and with different geometric accuracy and informational content, is what [13] did when modelling the cracks of the Santa Maria del Fiore dome in Florence. They developed two complementary HBIM sub-models: a detailed, realistic version suited to precise sensor placement and damage interpretation, and a simplified version designed for export and integration with external structural analysis tools. Each retains specific functions and data, remaining separate but interoperable.

Another approach that could be adopted is to use the survey data (typically the point cloud) as a sub-model that accurately represents the building’s geometry and then create an architectural model in BIM authoring software in which to develop a simplified geometric representation of the asset. The coexistence of the two models guarantees formal geometric accuracy and the possibility of managing a simplified model for the collection and storage of information, as well as the possibility of creating visualisations and designs based on the existing structure. This approach is followed, for example, by [14], who implemented two coordinated models: a survey-based model (i.e., the point cloud data managed through Autodesk Recap (version 2021)) that captures detailed existing geometry, and an ideal, simplified model (i.e., developed through parametric modelling in Autodesk Revit version 2021 software) used for information management. Aligned in the same reference system, they remain distinct yet interoperable, each serving different documentation and analysis needs. Particularly, the ideal model has a simplified geometry (i.e., lower geometric accuracy and fidelity), but has a high granularity, with each ashlar modelled as an individual parametric object, to enable more effective information management from a facility management perspective.

Similarly, in [15], a federated HBIM strategy is adopted by developing distinct but coordinated sub-models: a survey-derived geometric model (i.e., the point cloud managed through Autodesk Recap) and the architectural model (i.e., modelled within Autodesk Revit with various levels of detail). All models share a common spatial reference system and operate together within a maintenance-oriented digital ecosystem. This approach avoids a single unified model and allows each component to support specific documentation, analysis, and facility-management needs.

A slightly different approach is taken by [16], which created nine federated HBIM models from an integrated survey dataset, including general context models, multiple detailed area models (high-resolution segments of the urban context), and a parametric architectural model of the fortress. These were federated in Revit by importing each as a linked project with shared coordinates to maintain real-world georeferencing, enabling integrated contextual, detailed, and architectural information within a single coordinated environment.

The articles presented here show clearly how the federated model strategy in the field of HBIM can be used by different disciplines. They also highlight how, even within the same discipline, it is possible to manage different models in terms of level of detail, geometric representation, associated information, and purpose.

2.3. Automation and Visual Programming Language for BIM and HBIM Processes

BIM authoring software integrates, or allows integration with, Visual Programming Language (VPL) tools for the automation of various phases involving the BIM process. In the literature, we can find examples where such approaches are beneficial both for the

geometric modelling phase (including generative design), schedule management, report and table generation, or general information content management. These tools, such as Dynamo (version 2021) in the specific case of Autodesk Revit, are of great help in all those repetitive phases that, apparently, are more prevalent when modelling new buildings. For example, we can find studies in the scientific literature involving the use of Dynamo for the optimisation of the manufacture of construction elements, such as reinforcement bars for reinforced concrete; in the specific case of [17], the authors use VPL to model optimised reinforcement layouts and to generate schedules, with a workflow that enhances efficiency and reduces manual modelling effort. A similar case is that of [18], which models structural foundations in Autodesk Revit and uses Dynamo to calculate their weight and interface with Microsoft Excel to perform structural calculations. Another example is [19], which exploited Dynamo to automate modelling by extracting geometric data, matching columns to foundations, computing elevation differences, and adjusting base offsets.

In more complex workflows, VPL becomes useful both for generative design and for supporting the decision-making process. For example, ref. [20] showed that Dynamo in Revit can automate green roof analysis, enabling quick evaluations and informed design choices. Another example that demonstrates how VPL can assist in the informed management of complex building elements is that of [21], which uses Dynamo for Revit coupled with machine learning techniques to predict the required capacities of cooling and heating systems in detached houses, considering house geometry and its energy performance. Moreover, in road infrastructure design, there are examples of geometric modelling of complex linear elements based on actual geometric data, such as in [22], where Dynamo is used to import cross-sections extracted from point clouds, place parametric cross-section families along the road centreline with the correct rotation, and model them while preserving structure, alignment, and lateral gradient.

Although HBIM modelling often has to represent complex and unique cases, characterised by particular elements that are difficult to replicate, in the literature there are significant examples of repetitive actions even for HBIM. In such cases, VPL is an effective and sometimes indispensable tool, both in certain phases of the scan-to-HBIM process and in supporting the geometric and informational management of complex repeated or repeatable elements.

For example, ref. [23] focused on the reconstruction of BIM elements for a historic stone building surveyed using terrestrial laser scanning. From the point clouds, the authors employed Dynamo to extract geometric features (e.g., wall planes and openings) from the point cloud, classify them, and generate corresponding parametric BIM elements. With the same purpose of modelling by exploiting the point cloud data, in [24], the authors modelled historic timber trusses, starting from the point cloud, which was first interpreted and modelled parametrically in Grasshopper, where the geometry of each timber element (e.g., axes, nodes, and sections) was reconstructed. The resulting parametric model was then transferred into Revit through a Dynamo script, which mapped Grasshopper geometry to Revit family elements and generated the corresponding HBIM components automatically. Dynamo acted as a bridge, converting point-cloud-derived parametric geometry into native Revit objects while preserving dimensions, relationships, and attributes needed for documentation and structural analysis. Another interesting method for scan-to-HBIM (which, however, does not directly use a VPL, but uses external modelling software to support the model in Revit) is that presented by [25,26], which exploited NURBS curves to generate as-built parametric models from dense point clouds. NURBS curves were generated starting from the point cloud data by exploiting modelling software such as Rhinoceros or similar, then imported into Revit for the generation of surface-based families.

Within other studies, Dynamo is consistently employed as a VPL tool to automate the transfer, interpretation, and reconstruction of geometric information derived from point clouds within the BIM environment. In [27], Dynamo is used to generate vaults from parameters measured on the point cloud and input into the script. Dynamo constructs the vault parts and assembles all surfaces into a single vault geometry, which is finally imported into Revit as a DirectShape and checked against the point cloud. In [28], Dynamo is employed to semi-automate the modelling of architectural elements by converting classified point-cloud segments into boundary-representation (B-rep) geometries. The scripts read geometric primitives or profiles extracted from the survey, generate parametric solids for elements such as walls, slabs, and mouldings, and export them as Revit-compatible HBIM objects.

With regard to the use of VPL for modelling elements of historical architecture, referring to very specific rules from architectural theory, the contribution of [29] is interesting. They used Dynamo to encode the geometric rules of Vietnamese vernacular architecture and automatically generate Revit elements. The scripts take user inputs (e.g., building dimensions and roof parameters) and create or adjust columns, beams, and roof components, replacing manual modelling with rule-based parametric automation. Another example is that of [30], where Dynamo is used to parametrically generate the Doric column and its architectural members (shaft with entasis, flutes, echinus, abacus, architrave, etc.) from geometric ratios taken from the literature. The script builds these parts as a Revit family; the point cloud is then used only to measure and adjust the family parameters to fit the real column.

Remaining in the field of modelling and scan-to-BIM, VPL can also be useful for validating geometric models; for example, ref. [31] uses Dynamo and CloudCompare (version 2020) to sample points from the survey point cloud around selected elements, compute their distances to the Revit parametric models, and export these values to analyse geometric deviations and structural deformations.

Finally, focusing on pure information management in HBIM processes, we can find some contributions in the scientific literature, such as [32], where Dynamo was used to automate the population of an HBIM ontology, extracting parameters from the model and organising them into a semantic structure developed by the authors. Furthermore, in [33], Dynamo (version 2021) was used to automate and enable bidirectional data exchange between the HBIM model in Revit and external GIS/database environments. Custom scripts extracted and exported semantic, geometric, and spatial attributes from the HBIM model into an object-relational database and supported semantic alignment with GIS data.

Lastly, given its similarity to the case study presented in this article, it is interesting to analyse the management methodologies used in HBIM (e.g., geometric modelling and information management) not only for complex archaeological or historical sites, but also for just one of the parts that make up the site (i.e., the paving, as in the specific case study presented in this article). There is an interesting contribution concerning a historical road in Pompeii [34]. The geometry (a segment of Vicolo dei Balconi) was surveyed using terrestrial laser scanning and complemented by non-invasive ground tests to understand subsurface layers. After registration and segmentation, the model was built in Autodesk InfraWorks (version 2021) and Autodesk Civil 3D (version 2021), using custom cross-sections and property sets to represent both paved and unpaved areas. Dynamo was then employed to read these properties, automatically classify the different road segments, and colour-code them, enhancing the model's clarity and information management. Another study [35] focused on another road portion in Pompeii, the Via Stabiana, using a scan-to-BIM workflow. Point clouds were processed in InfraWorks, and custom Roman road cross-sections were modelled in Subassembly Composer and extruded in Civil 3D. Dynamo was used to

automate the updating of Property Sets, linking tabular data to the model. This allowed efficient management of semantic and geometric information, enhancing the archaeological analysis and conservation of the road.

2.4. Scopes of the Paper Within the Presented Context

The literature review highlights the progressive specialisation of HBIM research into complementary methodological directions, including information management, federated modelling, scan-to-HBIM automation, and domain-specific applications such as historical pavements (Table 1). These studies have significantly advanced individual aspects of the HBIM process, providing robust solutions to specific technical challenges and establishing the foundations for increasingly complex digital heritage workflows.

Table 1. Comparison between the main methodological directions emerging from the literature and the workflow proposed in this paper. Rather than comparing individual studies, the table summarizes the main research streams and highlights how the proposed methodology integrates them into a single framework.

Literature Contribution	Representative References	Information Management	Federated Models	Multi-Granularity Modelling	Automation (VPL/Scripting)	Construction-Site Support	Real Case-Study Implementation	Generalised Methodological Framework
Information management in HBIM	[32,33]	✓	○	–	✓	–	✓	–
Federated HBIM models	[12–16]	✓	✓	✓	–	–	✓	○
Automation of scan-to-HBIM processes	[23–31]	○	–	✓	✓	–	✓	–
HBIM for historical pavements	[34,35]	✓	○	✓	✓	○	✓	–
Proposed workflow	This work	✓	✓	✓	✓	✓	✓	✓

Note: ✓ = core component; ○ = partially addressed; – = not explicitly addressed.

However, these contributions generally address isolated methodological components. Although many are validated through real case studies, their primary objective is the development or demonstration of a specific solution rather than the definition of an integrated methodological framework. Consequently, there remains a need for workflows capable of systematically combining information management, federated models, multi-granularity modelling, automation, and construction-site support within a coherent methodology for complex conservation projects.

The present research addresses this gap from a different perspective. Instead of proposing a new modelling technique or automation procedure, it formalises the methodological knowledge generated during the conservation of the floor of the Holy Sepulchre Basilica into a generalised HBIM workflow. The scientific contribution therefore lies not in the introduction of a new technological component, but in the integration of existing methodologies into a structured and transferable framework, whose organisation is driven by the requirements of a real multidisciplinary conservation process. By abstracting the operational decisions, modelling strategies, data structures, and automation procedures developed for this project, the proposed workflow identifies a methodological sequence that

extends beyond the specific case study and can support the planning and implementation of other complex heritage conservation projects requiring multidisciplinary coordination, heterogeneous datasets, and long-term information management.

3. Federated HBIM Implementation for the Holy Sepulchre Basilica Conservation Project

3.1. Case Study Description, Operational Context and Requirements

The Basilica of the Holy Sepulchre in Jerusalem is a case study of exceptional importance due to its complexity, not only in terms of architecture, but also in consideration of its historical, cultural, and religious value. A fundamental site for Christianity, the architectural complex is the result of a long and complex historical stratification, extending from the Constantinian era to more recent interventions, passing through phases of construction, destruction, and reconstruction that have progressively shaped its current spatial configuration [36,37]. This stratification is not only architectural, but also cultural and functional, as the Basilica is still shared by several religious communities, each with its own rights, customs and modes of use. This condition makes any intervention particularly delicate, requiring a constant balance between conservation, use and shared management.

The conservation project for the Basilica's floor was conceived within this complex and constrained context. In 2019, a multidisciplinary intervention project was defined to address the conservation issues that had emerged over time. The overall coordination and drafting of the conservation project were assigned to the Conservation and Restoration Centre (CCR) "La Venaria Reale". The Department of Ancient Sciences at Sapienza University of Rome was tasked with conducting archaeological investigations, while the CNR-ISPC (Institute of Cultural Heritage Sciences) contributed its specific expertise in the study and characterisation of materials. Environmental monitoring was carried out by the CNR-ISAC (Institute of Atmospheric and Climate Sciences), while "IG - Ingegneria Geotecnica" was responsible for assessing the stability of the Aedicule of the Holy Sepulchre and structural safety measures. The design and implementation of the technical and technological systems were entrusted to "Manens-TIFS Ingegneria". Finally, the Department of Architecture, Built Environment, and Construction Engineering of Politecnico di Milano was assigned the task of developing HBIM and the data management plan, with the aim of managing the large amount of data produced and shared by the various units involved in the project in an integrated and consistent manner.

The Basilica's floor (partially visible in the left in Figure 1) is one of the most vulnerable elements of the entire complex, both for its historical and symbolic value and for the functional role it continues to play on a daily basis. It is subject to intense foot traffic from pilgrims and visitors, as well as daily liturgical practices. In addition to these stresses, there are specific factors contributing to its deterioration, such as the presence of wax from processions, the intensive use of detergents, and the overlapping of maintenance interventions that were not always coordinated over time. The result is a highly uneven surface, characterised by fragmented tiles, successive additions, and large areas of restoration, which compromise the overall legibility of the floor and necessitate a carefully planned conservation strategy.

In this context, the case study is not only the Basilica, but also the application and implementation of the floor conservation project according to HBIM logic. The need to simultaneously manage heterogeneous data, different actors and overlapping operational phases has highlighted the need for a structured approach capable of integrating geometric modelling, information and decision-making processes within a single coherent system. The federated HBIM model, thus conceived, becomes not only a representation tool, but also a dynamic environment supporting knowledge, design and conservation over time.



Figure 1. Photogrammetric survey workflow adopted for the documentation of the Basilica floor. **(Left):** field acquisition using the custom mobile photogrammetric prototype developed by Politecnico di Milano, showing representative surveying operations and examples of the conservation condition of the pavement. **(Right):** photogrammetric processing in Agisoft Metashape (the language of the software was set to Italian, so the text in the screenshot is Italian, but it is not meaningful for the content of the image), including image alignment, dense point cloud generation, and the resulting high-resolution orthophoto of the Basilica floor, with a detail of the final orthophoto.

3.2. Initial Data and Their Integration

The conservation project for the floor of the Basilica of the Holy Sepulchre was based on a complex set of heterogeneous data, drawn from historical sources, previous surveys and new acquisition campaigns developed specifically to meet the knowledge requirements that emerged during the course of the project. The integration of this information was a crucial phase, as it made it possible to build a solid and coherent knowledge base, which was essential to support the subsequent phases of modelling, design and management of the intervention.

Over the centuries, the Basilica has been the subject of numerous historical and archaeological investigations that have contributed to the understanding of its architectural transformations. The main construction phases, starting with Constantine's building in the 4th century [36,37], have been reconstructed thanks to stratigraphic studies and excavation campaigns conducted, in particular, by the Franciscan Virgilio Corbo [38] from the 1960s. His research, which is still fundamental today, has made it possible to interpret the complex succession of interventions that have affected the complex, many of which are still visible in the texture of the current floor. More recently, Geomatic surveys conducted by a team from the University of Florence [39] have been added to this, with the purpose of better monitoring and analysing the stability of the church after earthquake events.

A further significant contribution to the knowledge base was provided by the recent restoration of the Aedicule of the Holy Sepulchre [40], during which valuable diagnostic and structural data were acquired. Static and dynamic investigations, analyses of stone materials, and information on construction techniques provided essential reference points for understanding the mechanisms of deterioration and defining compatible and sustainable intervention strategies.

Starting from this consolidated knowledge base, the floor conservation project necessitated the acquisition of new data specifically aimed at understanding the walkable surfaces and their interactions with the underlying structures and systems. In particular, it was necessary to integrate updated geometric information, material data, and technical surveys relating to the technical infrastructure and fixed elements present on the flooring. The first contribution was a laser scanner survey carried out with Faro Focus X330 equipment (FARO Technologies, Inc., headquartered in Lake Mary, FL, USA) by architect Osama Hamdan, then technical manager of the Custody of the Holy Land, under the scientific coordination of the team from Politecnico di Milano. The survey covered the main areas of the Basilica, including the underground areas, and was supported by the positioning of topographic targets useful for defining a stable topographic reference network, which was subsequently used to georeference all subsequent acquisitions.

Subsequently, the team from Politecnico di Milano performed a high-resolution photogrammetric survey of the floor (Figure 1, left). This acquisition was designed to respond to particularly complex operating conditions: the need to operate during opening hours, the impossibility of interrupting liturgical functions, and the presence of highly reflective surfaces. To address these critical issues, a mobile photographic prototype was developed, designed as a controlled and isolated environment, equipped with a lighting system based on cross-polarisation [41,42]. The resulting system consists of a mobile platform integrating a high-resolution DSLR camera, a controlled LED lighting system, cross-polarization filters, and a blackout enclosure that isolates the acquisition area from ambient illumination. The camera is maintained at a fixed distance and orientation with respect to the surveyed surface, while the integrated lighting ensures stable and repeatable illumination conditions throughout the acquisition process. By combining controlled imaging geometry, homogeneous illumination, and standardized acquisition procedures, the system provides high-resolution and radiometrically consistent photogrammetric documentation suitable for the detailed recording of complex historic floors and other horizontal heritage surfaces. Metric accuracy was granted by a supporting topographic network materialized on the floor by ground control points measured by a total station. This solution made it possible to drastically reduce reflections and obtain chromatically consistent images, which were subsequently corrected using colorimetric boards. The result [43] was an orthophoto of the floor with a final pixel size of 0.5 mm (Figure 1, right), obtained from over 50,000 images acquired in multiple sessions and processed in several processing projects.

At the same time, other project partners contributed with additional specialist investigations. Georadar surveys made it possible to analyse the stratigraphy beneath the floor [44], providing useful information on the relationship between the flooring and the substructures. Structural analyses allowed for an initial assessment of the behaviour of the Aedicule and the surrounding areas, while surveys of existing systems and manholes provided essential data for planning the operational phases of the construction site. Finally, the “La Venaria Reale” Conservation and Restoration Centre conducted a detailed survey of the state of conservation of the stone materials, mapping degradation, alterations and petrographic characteristics useful for driving conservation choices.

3.3. Implementation of the Federated HBIM Architecture: Sub-Models, Automation, and Data Management

The complexity of the project, combined with the multiplicity of actors involved and a great heterogeneity of data, made it necessary to adopt an approach capable of managing different levels of information granularity. The HBIM model had to support both an overall view of the architectural structure and a highly detailed analysis of the floor, its components and its state of conservation. Furthermore, the system had to remain open and updatable, so that it could accommodate new data over time and possibly accompany and assist

the conservation interventions as well as the future life cycle of the building. With this in mind, the federated model was not conceived as a simple digital representation, but as a methodological framework capable of integrating skills, data, and decision-making processes, supporting all the disciplines involved in the intervention.

To ensure shared and consistent information management, Autodesk Revit 2021 was adopted as the BIM authoring platform, together with a CDE based on the former Autodesk BIM 360 platform (now Autodesk Construction Cloud). The selection of this software ecosystem was primarily driven by the operational requirements of the conservation project. Several datasets and preliminary models had already been developed using Autodesk software by different project partners, making it advantageous to adopt a common environment that ensured continuity throughout the project while avoiding unnecessary data migration and duplication. More importantly, the use of a single BIM authoring platform and a shared CDE provided all stakeholders—including architects, surveyors, restorers, structural and MEP engineers, archaeologists, and contractors—with a common information environment in which heterogeneous datasets could be progressively integrated, coordinated, and managed.

The CDE was structured to provide different levels of access and interaction according to the roles and responsibilities of the various users, while ensuring version control, traceability of modifications, and controlled information sharing. This organisation enabled the federated models and their associated documentation to be consulted, updated, and coordinated throughout the different phases of the project, from design and conservation activities to construction-site support. Given the multidisciplinary nature of the project and the involvement of international partners adopting different professional practices and national BIM implementation frameworks, the workflow was intentionally not constrained to a specific interoperability standard. Rather than enforcing a single exchange format, priority was given to establishing a shared collaborative environment capable of integrating heterogeneous datasets and supporting the operational needs of all disciplines throughout the conservation process.

The architecture of the HBIM model was divided into a series of coordinated sub-models (Figures 2 and 3), each with a specific function.

- The architectural context model (*ContextModel*) acted as a container for defining the surrounding conditions and delimiting the spaces within which all other sub-models were positioned.
- The floor was modelled at two different levels of detail:
 - a first sub-model (*FloorModel*) represented the pavement subdivided into macro-areas;
 - a second sub-model (*FloorTilesModel*) achieved the highest level of detail by representing individual tiles and fragments as single objects.
- The plant engineering model (*MEPModel*) contained information on manholes and underground services and was linked to the *ContextModel* and, depending on operational needs, to both floor models (*FloorModel* and *FloorTilesModel*).
- The structural analysis model (*STRModel*) referred exclusively to test results related to the Holy Sepulchre and maintained relationships only with the *ContextModel* and the *FloorModel*.

The *ContextModel* was built from laser scanner surveys and existing CAD drawings and included the common spaces of the Basilica up to a height of 2.50 m from the floor. This model also included the underground spaces and archaeological evidence documented during previous excavation campaigns, providing the spatial reference for all other models. System families were used for the geometric modelling of these elements, and above all,

elements were modelled in-place. Then, metadata relating to the source of the survey, function and available documentation (paper, digital, historical, photographic) were associated with each modelled element, allowing for an integrated reading of existing information and documents. The survey data (i.e., the point cloud database from photogrammetric and laser scanning acquisitions) were arranged into various Autodesk ReCap files in order to serve as an accurate geometric basis and imported into this first model.

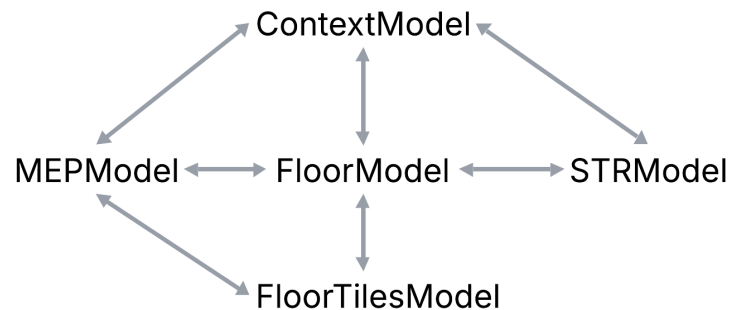


Figure 2. Scheme of the federated HBIM model architecture and sub-model relationships. The *ContextModel* represented the main architectural elements of the building and served as a basis for all the others. The floor was conceived as being formed by two different sub-models: *FloorModel* with floor macro-areas, and *FloorTilesModel* with higher granularity. Other models were the Structural *STRModel* and the technical systems model *MEPModel*.

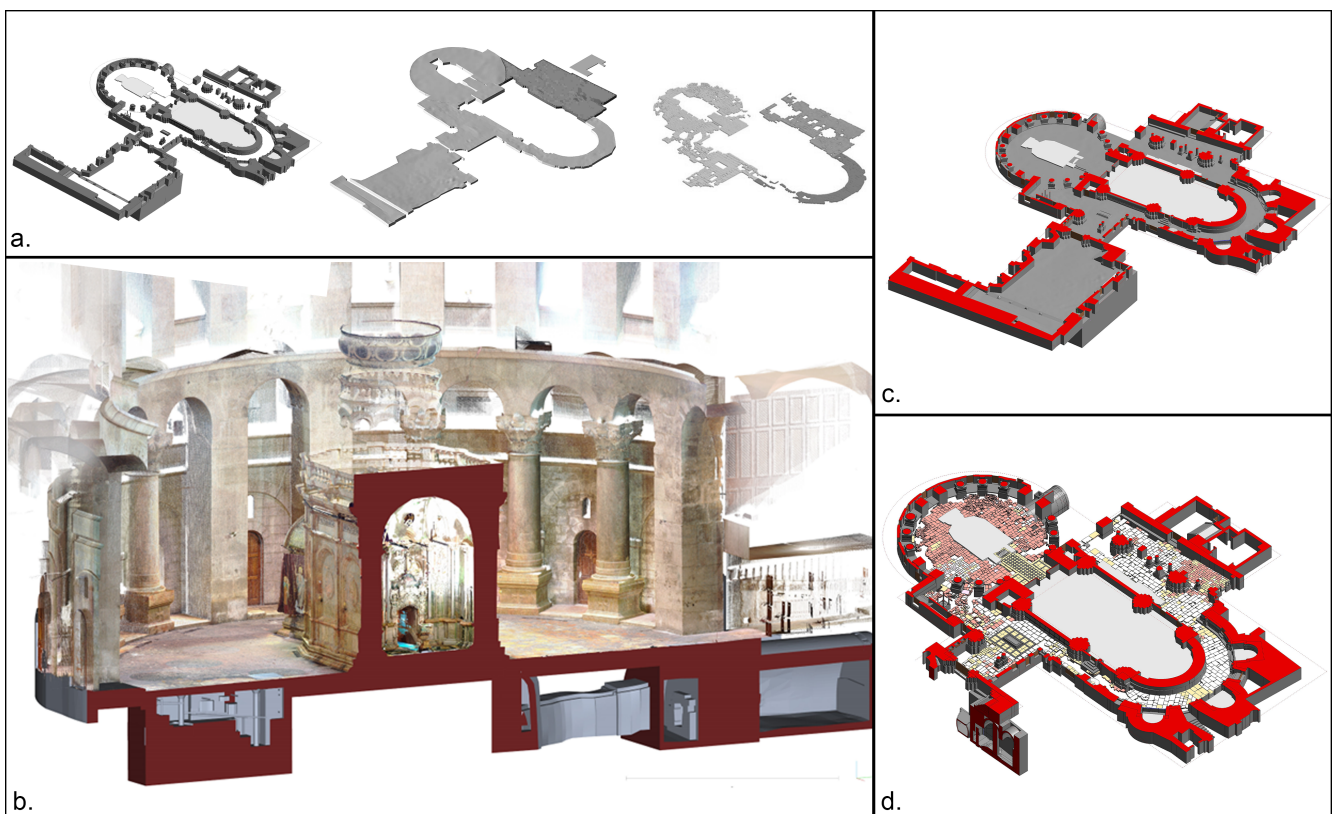


Figure 3. Federated HBIM models developed to support the conservation project. (a) Main operational sub-models composing the federated architecture: the *ContextModel*, *FloorModel*, and *FloorTilesModel*. (b) Integration of the *ContextModel* and *FloorModel* with the terrestrial laser scanning point cloud used as a geometric reference. (c) Federated view combining the *ContextModel* and *FloorModel*. (d) Federated view combining the *ContextModel* and *FloorTilesModel*, highlighting the multi-granularity organisation adopted for the conservation workflow. The tiles here are colored according to the identified material.

The *FloorModel* was created using mesh surfaces derived from high-resolution photogrammetric surveying. A modelling approach similar to that presented by [25] was used. The photogrammetric point cloud, resampled to 1 cm, was used as the basis for generating the NURBS using Rhinoceros software. The surfaces thus generated were then inserted into Revit as elements of the “mass” family and used to create a wall “by face”. The choice of modelling a floor by using the “wall family” was dictated by the need to create a geometry which followed exactly the mesh shape. The “wall by face” family was the only one with sufficient flexibility to achieve the purpose. The surfaces created were organised into functional macro-areas, consistent with the subdivision adopted in the conservation project. This model allows heterogeneous information, such as orthophotos, georadar data, materials overview, and historical references, to be associated with each macro-area.

Although the adopted modelling strategy does not preserve the semantic classification of a floor element in IFC-based exchanges, this did not affect the objectives of the proposed workflow. As discussed at the beginning of this section, the project prioritised a shared collaborative information environment over compliance with a specific interoperability standard, and the *FloorModel* was conceived as the geometric and informational reference for the conservation process rather than as an IFC exchange model. The selected modelling approach therefore represents an implementation choice made to satisfy the geometric and operational requirements of this specific conservation project.

The geometric accuracy of HBIM models is commonly assessed by comparing the generated model against the reference survey, typically through cloud-to-model distance analyses or equivalent geometric comparison procedures, as reported in previous Scan-to-HBIM studies [14,31,45]. Following the same approach, the geometric accuracy of the *FloorModel* was evaluated against the original photogrammetric point cloud. The validation strategy was intentionally differentiated according to the purpose of each federated sub-model. Since the *FloorModel* represents the primary geometric reference supporting the conservation project, it was quantitatively validated against the reference survey. Conversely, the high-granularity *FloorTilesModel*, described in the following paragraphs, derives directly from the orthophoto used for conservation mapping, and its geometric consistency was therefore verified through the correspondence between the vector representation and the reference orthophoto rather than through an independent cloud-to-model comparison. The remaining sub-models were developed to support organisational and discipline-specific information management rather than to provide independent geometric representations of the surveyed asset and therefore did not require the same quantitative validation procedure.

The validation of the *FloorModel* was performed by exporting the Revit surfaces as STL meshes and comparing them with the reference photogrammetric point cloud in Cloud-Compare (version 2021) using the Cloud-to-Mesh tool [46]. The resulting deviation map (Figure 4) showed average discrepancies below 1 cm, confirming that the adopted modelling strategy preserved the geometric accuracy required for the conservation activities.

The *STRModel* was developed as the dedicated federated sub-model for managing structural information related to the Holy Aedicule. Rather than performing structural analyses within the HBIM environment, its purpose is to spatially organise and archive the results produced by the structural engineering team. For this reason, the model consists of a simplified representation of the Aedicule, whose geometry was intentionally reduced to the minimum level required for the correct localisation of structural investigations while facilitating the readability of the associated information. At the current stage of the project, the model contains the results of the structural tests performed before the conservation works. Since the conservation project is still ongoing, the model has been designed to ac-

commodate possible future investigations and monitoring campaigns, allowing additional structural information to be progressively integrated as new data become available.

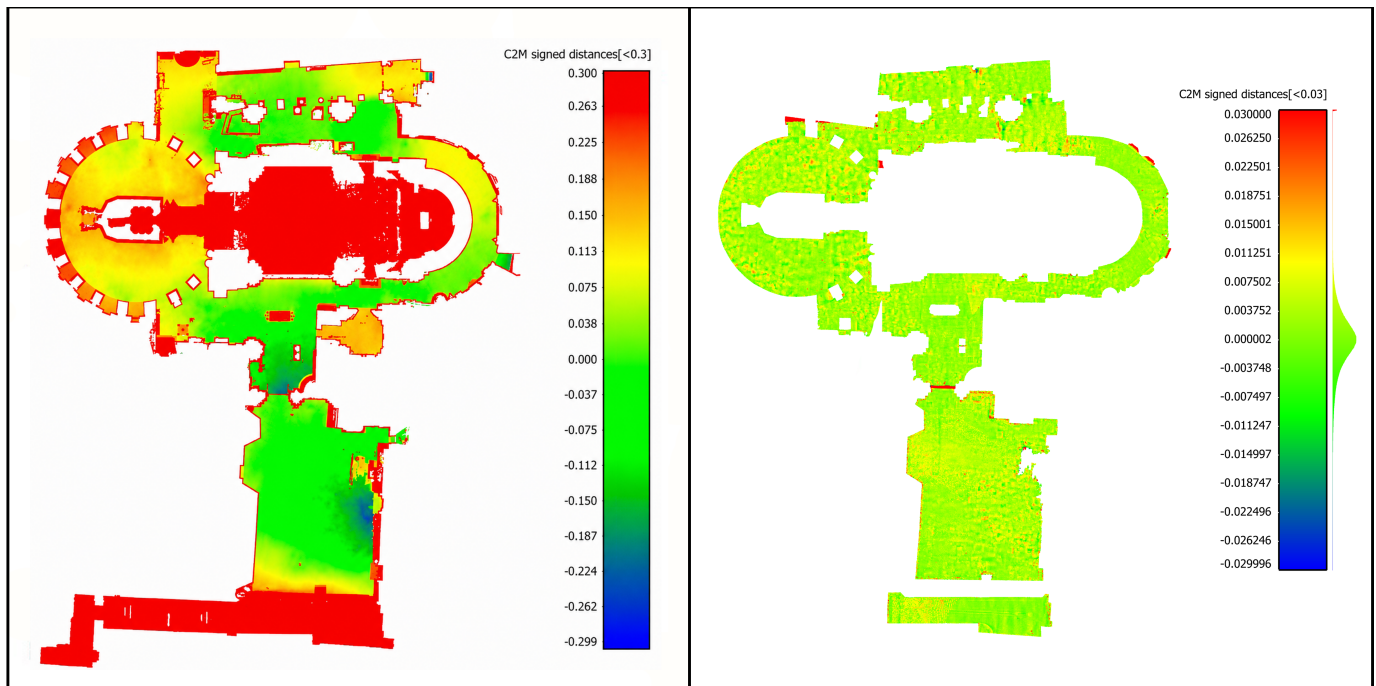


Figure 4. (Left): Photogrammetric point cloud of the Basilica's floor in false colours showing the elevations, orthographic top view. The zero elevation point has been positioned at the entrance to the church in front of the outer courtyard and is marked by a white cross. The scale bar is in meters. (Right): Deviation between the *FloorModel* and the photogrammetric point cloud of the floor in false colours, orthographic top view. The red areas are stairs or steps surveyed but not present in the model. It is clearly visible that the range of deviation is in the centimeter range. The color scale is in meters.

The *MEPModel* was conceived as the dedicated environment for managing information related to the underground technical systems associated with the new floor. Since the design and installation of the technical facilities can only be carried out after the removal of the existing pavement and the completion of the archaeological excavations, this sub-model is currently prepared but only partially populated. At the present stage, it contains the existing manholes surveyed on site together with the spatial framework required for the subsequent design activities. As the conservation project progresses, the model will be progressively updated with the design of the new technical systems, the as-built position of the installed utilities, and the point clouds documenting the excavation and installation phases. The shared coordinate system adopted by the federated HBIM architecture ensures the spatial consistency of these future updates with the remaining sub-models.

The maximum granularity was reached by the *FloorTilesModel*, which represented each individual tile and fragment of the floor as a single object. That was a specific requirement dictated by conservation needs. Starting from the AutoCAD (version 2021) drawings produced by the 'La Venaria Reale' Conservation and Restoration Centre exploiting the orthophoto, each tile and fragment was modelled as an independent object and enriched with specific information attributes (Figure 5): unique identifier, geometry, material, state of conservation, intervention hypothesis, and dimensional data. Given the large number of elements (over 3800), it was necessary to develop and implement automated procedures based on Dynamo (version 2021) and Python (version 3.9) scripts, which made it possible to generate the objects, assign parameters, link documentation and organise information in a systematic way. This approach allowed the completion of operations that would have

required a much greater amount of time with manual methods (a few hours instead of several days), while ensuring consistency and traceability.

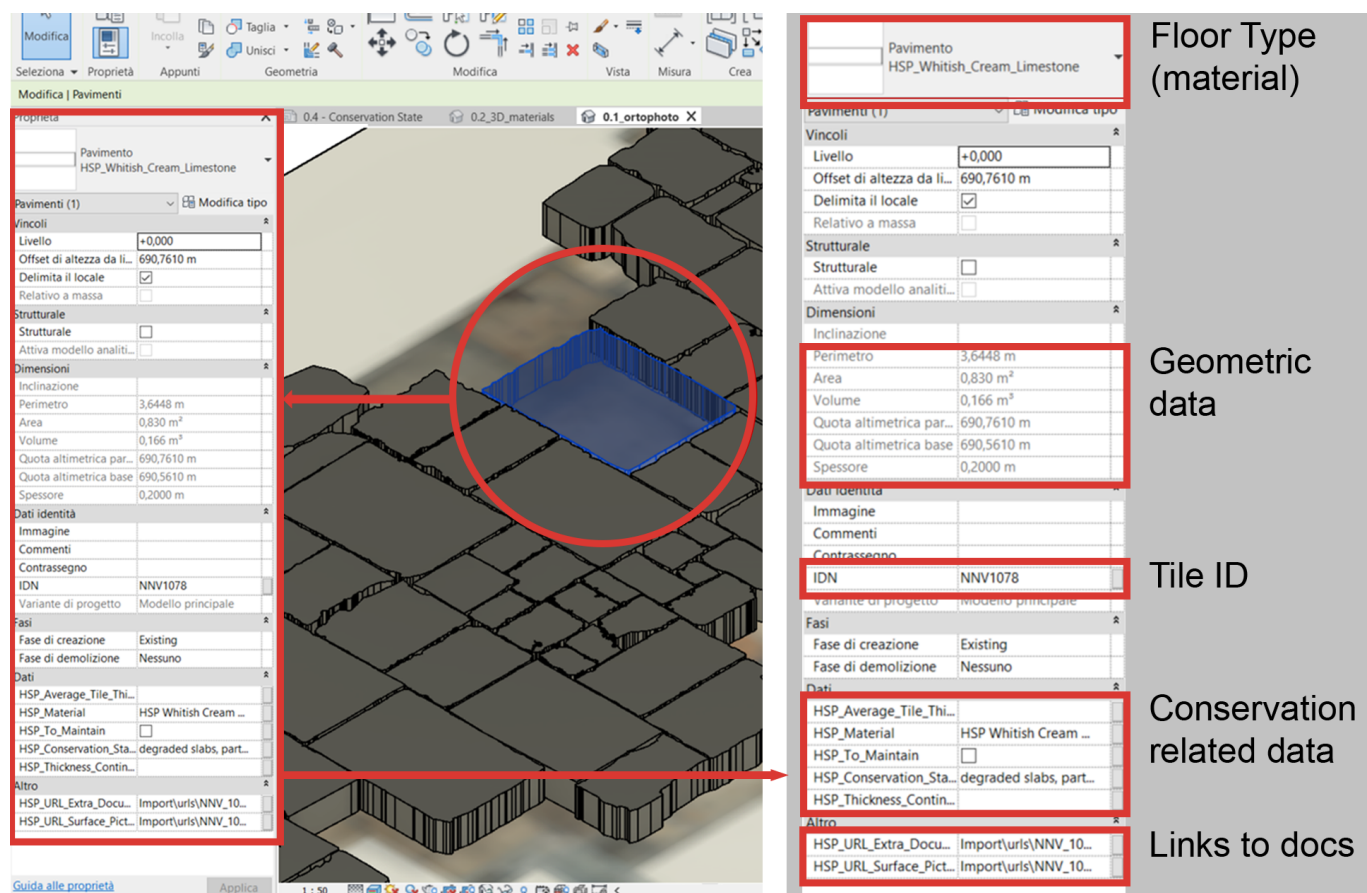


Figure 5. Screenshot of Autodesk Revit showing a portion of the detailed model with each tile modelled. The attributes associated with each element can also be viewed. Since the software was used in Italian language, the numbers follow the Italian rules, for the content and the significance of the image the numbers are not meaningful.

In particular, the automation strategy (workflow in Figure 6) began with the mapping analysis produced in AutoCAD by the ‘La Venaria Reale’ Conservation and Restoration Centre team, consisting of closed polylines and hatches describing the geometry of each tile and fragment, organised into thematic layers according to material and conservation characteristics. Using scripts developed in Dynamo and Python, each polyline was translated to its correct elevation, obtained by directly querying the photogrammetric point cloud, thus ensuring geometric consistency between the model, the survey data, and the shared reference system of the entire project. For each polyline, the point closest to each vertex and to the centre of the polyline was searched for in the point cloud, and their average Z value was assigned to the polyline itself.

Once correctly positioned in space, the geometries were extruded and converted into ‘floor element’ types within the Autodesk Revit environment, preserving their actual shape and allowing them to be associated with parametric attributes. Through further automated procedures, each element was enriched with information attributes derived from the project and conservation data, including a unique “ID” parameter (consisting of an initial letter identifying the area and a sequential number), material (derived from the layer and hatch to which it belongs in AutoCAD), conservation status (derived from the layer to which it belongs in AutoCAD), intervention indications and geometric parameters. At the same time, digital folders associated with each individual tile (named according to the ID) were

automatically generated and linked directly to the model by means of dynamic links (URL-type parameters). Automation not only saved a considerable amount of time compared to manual modelling, but above all ensured a high level of consistency, traceability and repeatability of the process, enabling the structured management of over 3800 elements.

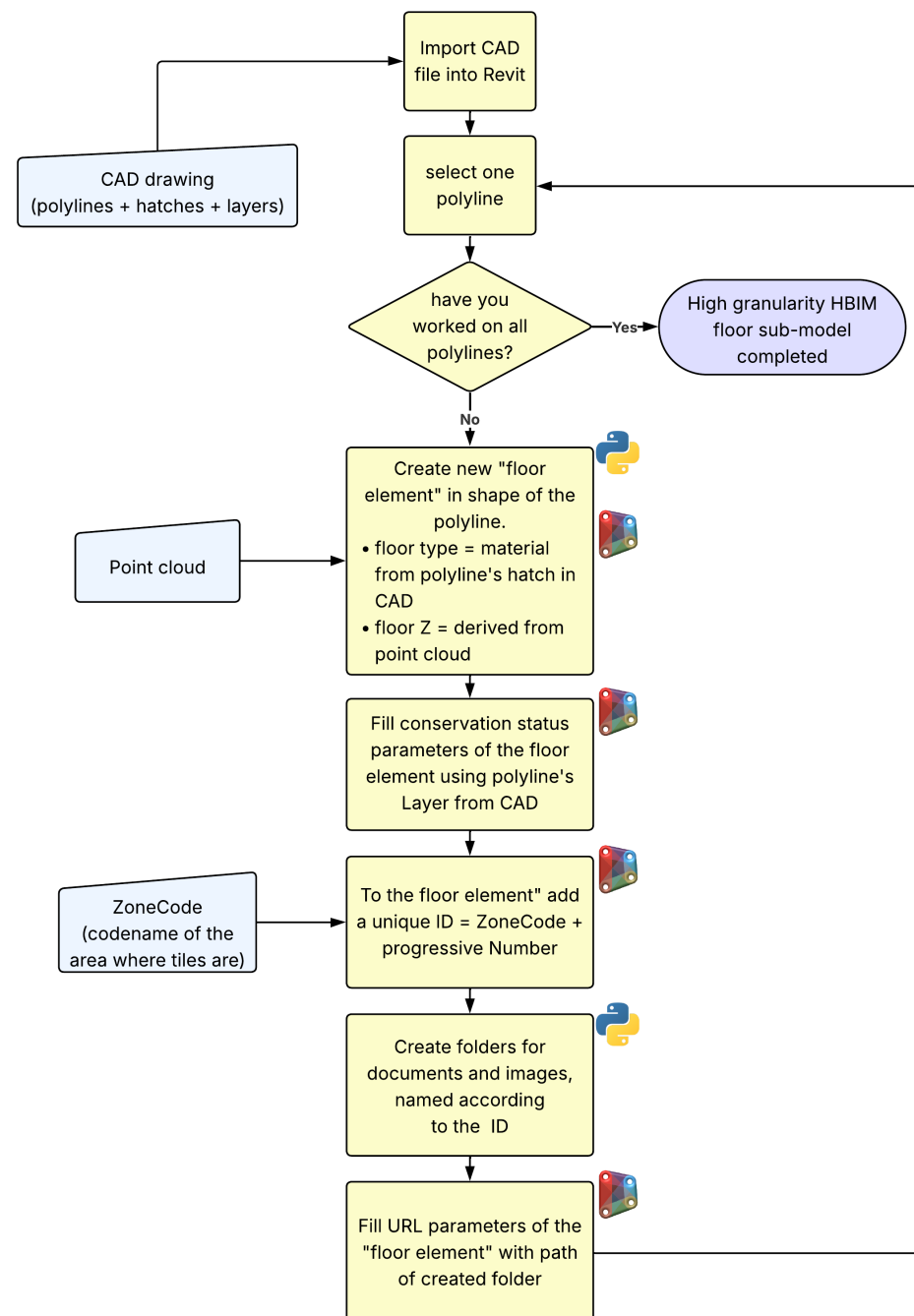


Figure 6. Automation workflow for the generation of a high-granularity HBIM model of floor tiles and fragments. The process integrates CAD vector data and photogrammetric point clouds through Python and Dynamo scripts to automate geometric positioning, element creation, information assignment, and linking to external documentation.

3.4. Operational Use of the Federated HBIM System

At the time of writing, the conservation project of the Basilica floor is still ongoing. Consequently, the long-term operational use of the federated HBIM system cannot yet be fully assessed. Nevertheless, the first phases of the intervention already provided

the opportunity to verify the proposed information management approach through its application during the ongoing conservation works.

One of the first operational applications concerned the conservation of the Basilica floor. During the removal of the stone tiles, conservators from the Centro Conservazione e Restauro “La Venaria Reale” progressively collected additional information that could not be fully assessed during the preliminary survey phase, including material verification, thickness measurements, and decisions regarding the subsequent conservation treatment of each individual tile. These observations were organised in spreadsheet format and imported into the HBIM model by matching the unique identifier assigned to each tile with the corresponding model element (Figure 7). This procedure enabled the automatic population of the relevant Revit parameters, allowing information generated directly on site to be systematically incorporated into the federated information system in a structured, traceable, and consistent manner.



Figure 7. Operational use of the federated HBIM system during the conservation works. **(Left):** documentation sheets automatically generated from the FloorTilesModel to support on-site data collection. **(Right):** detail of a documentation sheet showing the unique BIM identifier (ID) assigned to each floor tile. The same identifier is used to associate conservation records collected during the intervention with the corresponding HBIM element, enabling the automatic reintegration of updated information into the federated model.

At the same time, the federated architecture enabled the parallel development of the discipline-specific sub-models by the different project partners. In particular, the engineering team responsible for the technical systems continued updating the dedicated MEP sub-model by integrating new point clouds documenting the excavation progress together with the progressively defined technical installations. Since all sub-models share the same reference system, these updates could be incorporated while preserving spatial consistency across the overall federated model and without affecting the work carried out by the other disciplines.

Although these activities currently represent only the first stages of the construction process, they demonstrate that the proposed federated HBIM architecture can effectively support the progressive integration of multidisciplinary information generated during conservation activities. As the intervention proceeds, the information system will continue to be enriched by the different project partners, further extending its role as the shared digital environment for the management of the Basilica throughout the remainder of the conservation project.

4. From Case-Study Implementation to a Generalised Federated HBIM Workflow

The HBIM implementation described in Section 3 was developed to address the specific requirements of the Holy Sepulchre Basilica conservation project. Although developed for a unique and highly complex conservation scenario, the resulting methodological principles extend beyond the specific case study. By abstracting the methodological decisions, their interrelationships, and their role within the overall information management process, the practical experience has been formalised into the generalised federated HBIM workflow presented in this section. Rather than describing project-specific operations, the following workflow defines a methodological framework that can support comparable multidisciplinary heritage conservation projects.

The proposed methodology is organised into four sequential and interconnected steps (Figure 8). It begins with the definition of project requirements and modelling objectives, followed by the acquisition and organisation of heterogeneous datasets. These provide the basis for the development of a federated HBIM architecture integrating geometric modelling, information management, and automation strategies. Finally, the workflow extends beyond model development by supporting construction-site activities while ensuring information continuity throughout the subsequent conservation and facility management phases.

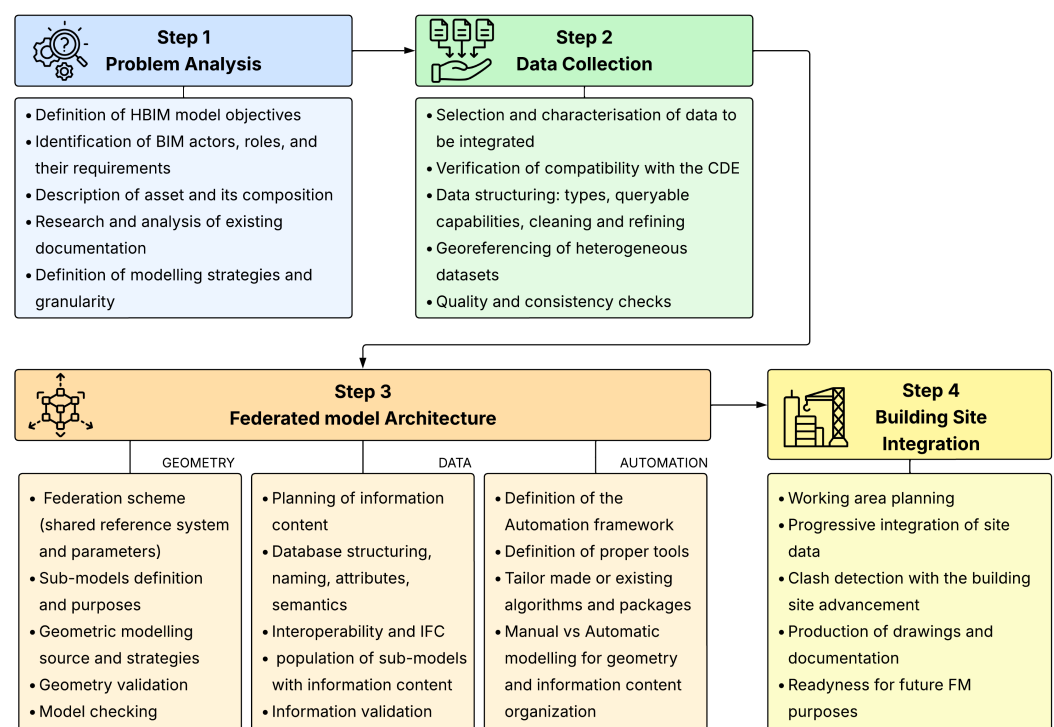


Figure 8. Generalised federated HBIM workflow derived from the implementation developed for the conservation project of the Holy Sepulchre Basilica.

4.1. Step 1—Problem Analysis and Workflow Definition

As shown in the general workflow (Figure 8), the first step establishes the conceptual and organisational framework that guides the entire HBIM implementation. Before any acquisition or modelling activity is undertaken, the objectives of the conservation project, the intended role of the HBIM system, and the corresponding information requirements are defined.

These decisions determine the federation strategy, including the identification of the required sub-models, their purposes, modelling granularity, and information content.

At the same time, the organisational framework is established by assessing the available documentation, identifying stakeholders and responsibilities, and defining the collaborative environment in which information will be managed throughout the project.

The relationships between project requirements, methodological decisions, and expected outcomes for this phase are summarised in Figure 9.

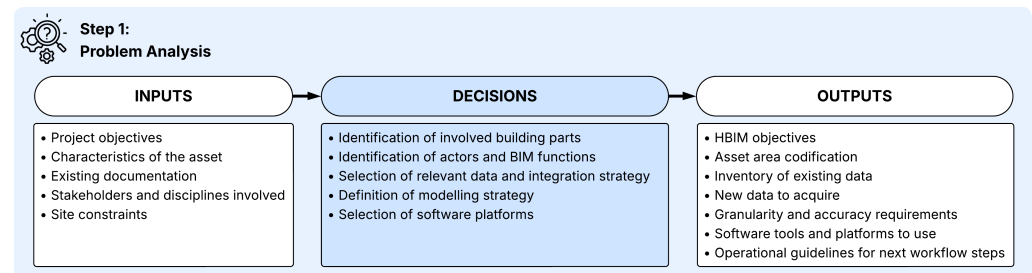


Figure 9. Methodological structure of Step 1 according to the input–decision–outcome framework.

4.2. Step 2—Multi-Source Data Acquisition and Organisation

Building on the strategy defined in Step 1 (Figure 8), the second phase prepares the information base required for the federated HBIM system. Rather than collecting all available documentation, the workflow focuses on selecting and organising the datasets that effectively support the conservation objectives.

Survey data, historical documentation, diagnostic investigations, archival records, and technical reports are evaluated according to their reliability, relevance, and intended use. Before modelling begins, heterogeneous datasets are harmonised within a common reference framework to ensure geometric, semantic, and organisational consistency, resulting in a structured information base that supports the subsequent HBIM implementation.

Figure 10 illustrates how data selection, validation, and harmonisation are translated into a coherent information base for the development of the federated model.

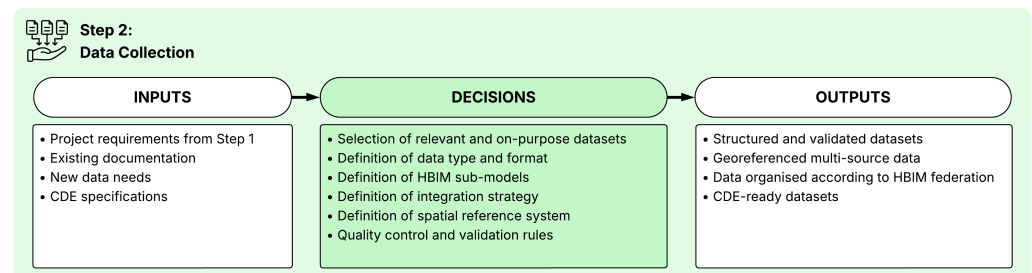


Figure 10. Methodological structure of Step 2 according to the input–decision–outcome framework.

4.3. Step 3—Federated HBIM Architecture Development

The third step (Figure 8) represents the core of the proposed workflow, where the methodological decisions and structured information produced in the previous phases are translated into an operational federated HBIM system. At this stage, the workflow shifts from planning to implementation, combining geometric modelling, information organisation, and automation within a coordinated framework.

The federated architecture is developed by creating independent but spatially coordinated sub-models, each designed to fulfil a specific purpose while contributing to a shared information environment. Rather than reflecting disciplinary boundaries alone, the subdivision into sub-models is driven by modelling objectives, information requirements, and the different levels of geometric and semantic granularity required by the conservation process. This approach allows multiple complementary representations of the same heritage asset to coexist while remaining consistently integrated.

Particular attention is devoted to the information architecture. Geometric elements are conceived as semantic entities capable of organising and linking heterogeneous datasets, including survey results, historical documentation, diagnostic investigations, monitoring records, and external resources. Consequently, the workflow defines coherent parameter structures, naming conventions, and relationships between geometric and non-geometric information, enabling the federated model to operate as a structured knowledge system rather than a simple three-dimensional representation.

Automation supports this process whenever repetitive modelling or information management tasks can be formalised into reusable procedures. Instead of representing an independent phase, automation contributes to improving consistency, reducing manual operations, and facilitating the management of highly granular datasets, while preserving the flexibility required by complex heritage conservation projects.

The methodological relationships between federated modelling, information architecture, and automation are summarised in Figure 11.

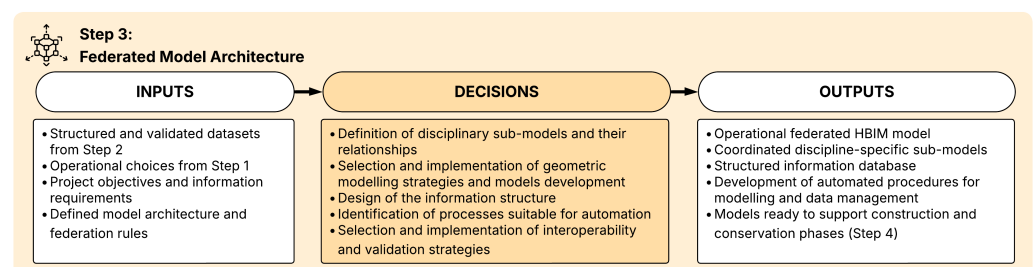


Figure 11. Methodological structure of Step 3 according to the input–decision–outcome framework.

4.4. Step 4—Operational Use and Lifecycle Information Management

The final step of the workflow (Figure 8) extends the federated HBIM system beyond model development, integrating it into construction activities and the subsequent lifecycle of the heritage asset.

As the conservation project progresses, information generated during construction (including inspections, technical decisions, modifications, and unforeseen conditions) is progressively incorporated into the federated environment, maintaining consistency between the physical asset and its digital representation. This continuous updating preserves the knowledge generated during the intervention and prepares the information system to support future monitoring, maintenance, conservation, and facility management.

Figure 12 highlights the relationship between operational activities, information updates, and long-term lifecycle management within the proposed workflow.

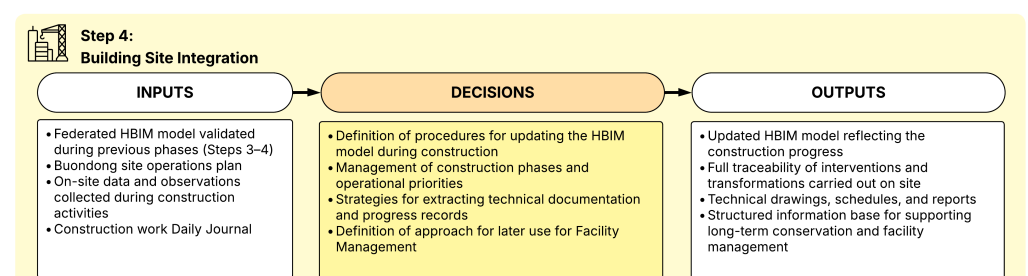


Figure 12. Methodological structure of Step 4 according to the input–decision–outcome framework.

5. Discussion

5.1. Scientific Contribution

While federated HBIM approaches have been adopted in heritage projects, they are often presented as project-specific implementations, making it difficult to generalise their

methodological principles. The workflow proposed in this study addresses this gap by formalising the organisational and technical decisions that emerged during a real multidisciplinary conservation project. Rather than prescribing specific modelling procedures or software environments, the proposed framework abstracts the methodological choices developed during the Holy Sepulchre project into a transferable workflow integrating information requirements, data organisation, federated modelling, automation, and operational use.

5.2. Federation as an Information Strategy

One of the main outcomes of this work is the interpretation of federation as an information management strategy rather than a simple subdivision of disciplinary models. Sub-models are defined according to their purpose, required geometric and semantic granularity, and expected evolution throughout the conservation process, allowing complementary representations of the same heritage asset to support different users and operational needs within a coherent information environment.

The case study demonstrated that this organisation was fundamental to obtaining an operationally usable HBIM system. Instead of concentrating all information within a single model, independent sub-models could evolve according to different objectives while remaining spatially and semantically coordinated. This proved particularly valuable in a project where archaeological investigations, restoration, structural assessments, MEP design, and construction activities progressed at different stages and required different levels of detail.

This strategy inevitably increases the effort required for model organisation, information management, and multidisciplinary coordination. However, in projects of this scale, the resulting flexibility largely compensates for the additional complexity. Rather than limiting usability through a monolithic model, the federated architecture provides a scalable information system capable of supporting different disciplines and project phases.

5.3. Standardisation, Interoperability and Implementation Choices

The implementation also highlighted the practical challenges associated with standardisation and interoperability in multidisciplinary conservation projects. Although semantic interoperability, open standards, and shared ontologies represent important objectives within the BIM community, their adoption may not always be compatible with projects involving multiple organisations operating according to different regulations, procedures, and digital workflows.

In the present case study, priority was therefore given to establishing a shared collaborative environment rather than enforcing a common ontology or exchange standard. This decision also motivated the adoption of Autodesk Revit and Autodesk Construction Cloud, providing a common authoring and information management environment while preserving the operational practices of the different stakeholders. Wherever possible, standard Revit system families were maintained; however, the geometric complexity of the project occasionally required modelling strategies that departed from ideal IFC-compatible representations, such as the workaround adopted for the floor model.

These choices should be regarded as implementation decisions rather than limitations of the proposed workflow. The experience suggests that, in highly collaborative conservation projects, interoperability is primarily an organisational challenge, requiring a balance between methodological consistency, operational usability, and the constraints of the participating organisations. The abstraction proposed in this work separates these implementation choices from the methodological framework, allowing it to remain transfer-

able while highlighting the need for future research on the integration of shared ontologies and open interoperability standards in similarly complex collaborative environments.

The organisational complexity of the project also emphasised the importance of automation. Rather than representing an accessory component, automation proved essential to making the proposed workflow operationally feasible. The high number of modelled elements, the continuous integration of heterogeneous datasets, and the progressive updating of information would have required an unsustainable amount of manual work. By automating repetitive modelling and information management tasks, the workflow improved consistency, reduced human error, and ensured the scalability of the federated model. Automation should therefore be regarded as an enabling component of complex federated HBIM workflows rather than simply as a productivity tool.

5.4. Generalisability and Limitations

Although derived from a single case study, the proposed workflow identifies methodological principles applicable to similarly complex heritage conservation projects. While many of these principles may appear familiar within conventional BIM practice, their systematic application becomes significantly more challenging in projects involving multiple disciplines, heterogeneous information sources, different modelling granularities, numerous organisations, and diverse technical, cultural, and operational frameworks. In this context, the proposed workflow provides a methodological reference for structuring collaboration rather than prescribing specific technical solutions.

Some limitations should nevertheless be acknowledged. The conservation project is still ongoing, and the federated HBIM system continues to evolve together with the intervention. Although the model has already supported several conservation activities and demonstrated its ability to accommodate new information, its use is progressively expanding as additional stakeholders become involved. Consequently, some components (particularly the complete implementation of the MEP sub-model and the long-term use of the system for facility management) will only be fully assessed after completion of the intervention. Further applications to different heritage contexts will also be necessary to evaluate the adaptability of the proposed workflow under different organisational and technical conditions.

5.5. Future Perspectives

The proposed workflow should therefore be regarded as an evolving methodological framework rather than a definitive solution. Future developments should focus on its application to additional heritage contexts, allowing the workflow to be progressively refined and adapted to different organisational scenarios. Further research should also investigate how shared ontologies and interoperability standards can reconcile the flexibility required by complex conservation projects with a more homogeneous information management approach across different stakeholders, further strengthening federated HBIM as a long-term information infrastructure.

6. Conclusions

This paper presented the development of a federated HBIM workflow for the conservation of the floor of the Holy Sepulchre Basilica, a complex ongoing heritage conservation project. Starting from the implementation of a real multidisciplinary case study, the research formalised a transferable methodological framework integrating information planning, multi-source data organisation, federated modelling, automation, and operational information management. The workflow identifies a sequence of methodological decisions

that can support the implementation of federated HBIM systems in similarly complex heritage projects.

The application of the workflow demonstrated that federation, when conceived as an information management strategy rather than a simple disciplinary subdivision, provides an effective approach for coordinating heterogeneous datasets, different modelling granularities, and multiple stakeholders within a coherent information environment. The case study also highlighted the fundamental role of automation in making the management of highly detailed federated models operationally sustainable, while showing that implementation choices should be adapted to the organisational requirements of each conservation project.

Although the workflow was developed from a single case study, its abstraction provides a methodological reference that can support future multidisciplinary conservation projects characterised by comparable organisational and informational complexity. Further applications will contribute to refining the proposed framework, while future research should investigate the progressive integration of shared ontologies and interoperability standards capable of strengthening collaborative information management without compromising the flexibility required by complex heritage conservation processes.

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