

Article

The Certosa di Pavia Digital Ecosystem: A Massive Multi-Scale Digitization Framework Integrating 3D Survey, HBIM, and VR for Long-Term Preservation and Knowledge Dissemination

Fabrizio Banfi ^{1,*} , Ezio Arlati ¹, Fabio Roncoroni ¹, Stefano Della Torre ¹ , Rosario Maria Anzalone ², Stefano Aiello ², Silvia Zanzani ², Marco Pela ¹ and Gabriele Minelle ¹

- ¹ Department of Architecture, Built Environment and Construction Engineering (DABC), Politecnico di Milano, (ABCLab-GICARUS), 20133 Milan, Italy; ezio.arlati@polimi.it (E.A.); fabio.roncoroni@polimi.it (F.R.); stefano.dellatorre@polimi.it (S.D.T.); marco.pela@mail.polimi.it (M.P.); gabriele.minelle@mail.polimi.it (G.M.)
- ² Direzione Regionale Musei Nazionali Lombardia, Ministero della Cultura (MiC), 20123 Milan, Italy; stefano.aiello@cultura.gov.it (S.A.); silvia.zanzani@cultura.gov.it (S.Z.)
- * Correspondence: fabrizio.banfi@polimi.it

Abstract

Digital technologies have significantly advanced documentation, management, and dissemination of Cultural Heritage (CH) through reality capture, Heritage Building Information Modelling (HBIM), and Extended Reality (XR). However, the digitisation of large and historically stratified heritage sites still relies on fragmented workflows that compromise interoperability and interrupt the continuity of geometric and semantic information throughout the heritage lifecycle. This paper proposes and validates a platform-independent, ecosystem-based methodology integrating multi-scale reality capture, hybrid Scan-to-HBIM modelling, semantic information management, interoperability, and XR within a continuous digital workflow. The methodology was validated through the large-scale digitisation of the Certosa di Pavia, where more than 1500 terrestrial laser scans, over 200,000 photographs, and approximately 50 billion points were acquired across a monumental complex covering nearly 331,000 m². The proposed framework reconstructs irregular architectural geometries with millimetre-scale accuracy ($\sigma = 0.005$ m) while preserving geometric reliability, semantic consistency, and information traceability across point-cloud processing, HBIM environments, Common Data Environments (CDEs), and XR applications. The results demonstrate that the effective digitisation of complex CH depends not only on the accuracy of individual technologies but also on their coordinated integration within interoperable digital ecosystems. The proposed methodology provides a transferable framework for preserving knowledge continuity throughout the heritage lifecycle, enabling HBIM to evolve from a geometric representation into a dynamic knowledge environment supporting conservation, management, research, education, and public dissemination.



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1. Introduction

1.1. The Certosa di Pavia in Transition: Toward an Ecosystem-Based Digital Heritage Framework

Digital technologies have profoundly transformed the documentation, analysis, conservation, management, and dissemination of Cultural Heritage (CH). Reality capture, Heritage Building Information Modelling (HBIM), and Extended Reality (XR) now enable

the acquisition, organisation, and communication of increasingly detailed geometric and semantic information, supporting applications ranging from conservation planning to public accessibility [1–7]. Despite these advances, many heritage digitisation projects still rely on fragmented workflows in which reality capture, modelling, semantic enrichment, information management, and visualisation are developed through software-specific procedures and heterogeneous data structures. As a result, information is repeatedly converted, duplicated, or simplified, reducing interoperability, semantic consistency, and the long-term usability of digital heritage datasets [8,9].

These limitations become particularly critical for large, historically stratified heritage complexes, where irregular geometries, heterogeneous construction techniques, and multiple historical phases generate highly heterogeneous datasets. In such contexts, the challenge is no longer limited to producing accurate three-dimensional models but to maintaining geometric, semantic, and documentary continuity throughout the digital lifecycle of the asset, enabling reliable information exchange across documentation, conservation, management, and dissemination processes.

The Certosa di Pavia provides an ideal context for investigating these challenges. Rather than a single monument, it is a complex architectural system comprising churches, cloisters, residential buildings, service areas, underground structures, roof systems, and hidden circulation spaces that have evolved over more than six centuries [3,4]. Its scale, architectural complexity, and historical stratification require an integrated methodology capable of managing heterogeneous datasets while preserving geometric reliability and semantic coherence across multiple levels of representation.

This research was developed within an institutional programme promoted by the Direzione Regionale Musei Nazionali Lombardia (Italian Ministry of Culture) to support the digital transition of the Certosa through integrated activities focused on documentation, conservation, management, and accessibility. Within this programme, a specialised team from the Department of Architecture, Built Environment and Construction Engineering (DABC) of Politecnico di Milano, with expertise in the digitisation of large-scale historic monuments, developed the reality capture strategy, the Scan-to-HBIM workflow, the interoperability protocols, and the XR applications.

Building on these challenges, the research investigates how an ecosystem-based approach can support the integration of reality capture, HBIM, interoperability, and XR within a coherent digital workflow for CH. The Certosa di Pavia is therefore adopted as a large-scale experimental testbed for assessing the feasibility of this approach.

The following section reviews the current state of the art and identifies the methodological gap addressed by the proposed research. Within this perspective, the Certosa di Pavia is adopted as a large-scale experimental testbed to validate the proposed framework and assess its capability to support the documentation, conservation, management, accessibility, and dissemination of complex CH assets. The following section positions this research within the current state of the art by reviewing recent advances and the remaining methodological challenges in CH digitisation.

1.2. From Linear Workflows to Digital Ecosystems: State of the Art and Current Challenges in CH Digitization

Over the past two decades, CH digitisation has undergone remarkable progress in both reality capture and digital modelling. The widespread adoption of terrestrial laser scanning (TLS) [10], close-range photogrammetry [11], UAV-based acquisition [12], and integrated multi-sensor survey strategies [13] has established the Scan-to-HBIM paradigm as a reference methodology for heritage documentation and conservation [14].

These technologies enable the acquisition of high-resolution geometric data across multiple spatial scales, supporting the accurate documentation of complex architectural

systems. However, research has largely focused on optimising data acquisition and model generation, while comparatively less attention has been devoted to maintaining information continuity beyond the survey stage. As reality-based datasets are transferred across modelling, documentation, and visualisation environments, repeated data conversions often generate duplicated information, fragmented digital assets, and reduced interoperability throughout the heritage lifecycle.

In parallel, HBIM has evolved from the adaptation of conventional Building Information Modelling (BIM) methodologies into a comprehensive environment for organising and managing heritage information. Beyond geometric representation, HBIM models increasingly integrate historical documentation, material characterisation, diagnostic investigations, conservation records, maintenance data, and archival sources, supporting multidisciplinary knowledge management [15–19]. This evolution has been reinforced by international standards and information management frameworks, including ISO 19650 [20], EN 17412-1 [21], and IFC-based interoperability protocols [22].

At the same time, advances in point cloud processing, cloud-to-model verification, parametric reconstruction, scan-to-BIM-to-FEM approaches and hybrid modelling have significantly improved the representation of complex architectural geometries [23–36]. Likewise, concepts such as Levels of Geometry (LOG), Levels of Information (LOI), Levels of Reliability (LOR), and Level of Information Need (LOIN) have progressively strengthened the semantic organisation of HBIM models [37–42]. More recently, Artificial Intelligence (AI) and Machine Learning (ML) have further enhanced architectural representation, point cloud segmentation, object classification, and semantic annotation [43–45]. Despite these developments, interoperability between modelling platforms remains limited.

Most commercial HBIM platforms remain based on parametric modelling paradigms originally developed for regular construction systems and therefore struggle to represent the irregular geometries, complex vaults, stratified masonry, sculptural elements, and morphological variability that characterise historic architecture.

Hybrid workflows combining BIM, NURBS, and mesh-based modelling have consequently become widespread. Although these approaches improve geometric fidelity, they often require additional data transformations that weaken the relationship between geometry and semantic information, reducing interoperability throughout the workflow.

The progressive enrichment of HBIM has also stimulated the development of Digital Twin (DT) approaches capable of integrating dynamic information, monitoring data, and multidisciplinary knowledge within digital representations of heritage assets [46–50]. However, most implementations remain confined to software-specific ecosystems, where semantic information is only partially preserved during data exchange and is frequently disconnected from downstream visualisation and dissemination environments.

In parallel, immersive technologies have extended heritage digitisation beyond documentation towards accessibility, interpretation, education, and public engagement. Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), WebXR, and, more broadly, Extended Reality (XR), have demonstrated considerable potential for virtual visits, remote accessibility, conservation communication, and the exploration of otherwise inaccessible spaces.

Landmark applications—including the Colosseum [51], the Acropolis of Athens [52], the Sagrada Família [53], Milan Cathedral [54,55], the Arena of Verona [56], the Basilica of San Marco in Venice [57], Matera [58], Pompeii [59], Herculaneum [60], Angkor [61], Petra [62], and the Appian Way [63,64]—demonstrate the growing maturity of digital technologies for the documentation, analysis, and management of CH. However, despite these advances, the fragmentation of digital workflows and data sources often compromises information continuity, semantic coherence, and long-term sustainability.

The limitations of fragmented workflows become even more evident in vulnerable or post-disaster contexts. Experiences at Notre-Dame de Paris [65], the Basilica of Collemaggio after the 2009 earthquake and reconstruction activities in L'Aquila [66,67] have proposed innovative digital approaches aimed at minimising information loss, improving documentation continuity, and supporting coordinated conservation and reconstruction processes through integrated and interoperable datasets.

Immersive technologies—including VR, AR, MR, and WebXR platforms—have further extended the role of digital heritage environments toward accessibility, interpretation, and public engagement [68,69]. However, survey datasets, HBIM models, GIS environments, and XR applications still frequently operate in disconnected processes, relying on heterogeneous formats and repeated data conversions. This condition often compromises information continuity, semantic coherence, and long-term sustainability.

While individual technologies have evolved considerably, their integration into coherent and interoperable workflows remains limited. There is therefore a growing need to move beyond fragmented and sequential pipelines toward ecosystem-based approaches in which datasets, modelling environments, semantic structures, interoperability protocols, and visualisation systems operate as interconnected components of a scalable digital infrastructure.

Within this perspective, interoperability should be understood not merely as technical compatibility between formats, but as a methodological condition underpinning the long-term conservation, analysis, management, accessibility, and dissemination of these technologies within the CH domain.

Nevertheless, XR applications are still predominantly developed as downstream visualisation environments through one-way export procedures from HBIM or geometric models, limiting the preservation of semantic relationships and structured information.

Overall, the literature shows that reality capture, HBIM, DTs, and XR technologies have reached a high level of maturity. However, these domains have largely evolved as independent research trajectories rather than as components of an integrated digital process.

Accordingly, the principal challenge is no longer the development of individual technologies, but the preservation of geometric, semantic, and informational continuity throughout the heritage lifecycle. Addressing this challenge requires moving beyond sequential, software-dependent workflows towards platform-independent digital ecosystems capable of integrating reality capture, hybrid Scan-to-HBIM modelling, semantic information management, interoperability protocols, CDEs, and XR technologies within a unified knowledge infrastructure.

1.3. Research Objectives and Contribution

Addressing the challenges identified in the current literature, this research proposes and validates a platform-independent, ecosystem-based framework for the digital management of complex CH assets.

The framework is evaluated through the Certosa di Pavia case study to assess its capability to support integrated CH documentation, management, and dissemination.

The framework has been developed and validated through the large-scale digitisation of the Certosa di Pavia, where reality capture, Scan-to-HBIM modelling, semantic information management, interoperability, and XR are integrated within a unified digital ecosystem supporting documentation, conservation, management, accessibility, and dissemination. Accordingly, the research pursues four main objectives:

- to develop an integrated methodological framework connecting multi-scale reality capture, Scan-to-HBIM modelling, semantic information management, interoperability protocols, and XR technologies;

- to evaluate the capabilities and limitations of current modelling platforms and interoperability strategies for representing complex CH geometries and managing semantic information;
- to validate interoperability strategies supporting the continuous exchange of geometric and semantic information among point cloud processing platforms, HBIM environments, CDEs, and XR applications;
- to assess the proposed framework through the digitisation of the Certosa di Pavia, evaluating its ability to preserve geometric accuracy, semantic consistency, interoperability, and information continuity throughout the digital workflow.

The scientific contribution of this study does not lie in introducing a new survey technology, modelling strategy, or visualisation platform. Instead, it demonstrates how existing technologies can be systematically integrated into a coherent and transferable digital ecosystem. The framework is evaluated through four complementary dimensions—geometric reliability, semantic consistency, interoperability, and information continuity—providing an operational methodology for reducing fragmentation between digital environments while improving the traceability and long-term usability of heritage information.

Although validated through the Certosa di Pavia, the approach is intended to be transferable to other large-scale and historically stratified CH assets, providing an interoperable framework for documentation, conservation, management, and dissemination.

2. Materials and Methods

2.1. Research Design and Methodological Framework

The proposed methodology is implemented through operational phases that progressively transform reality-based data into a structured digital knowledge environment (Figure 1). Rather than describing independent activities, the workflow organises data collection, HBIM reconstruction, semantic information management, and information sharing as interconnected processes supporting the continuous exchange of validated geometric and semantic information.

Accordingly, the framework is organised into four complementary phases (Figure 1):

(i) Data Collection. Integrated reality-capture techniques—including terrestrial laser scanning, photogrammetry, UAV acquisition, and topographic surveying—establish the geometric reference for the entire workflow through georeferenced and validated datasets.

(ii) Scan-to-HBIM. Survey data are transformed into structured HBIM models through point cloud processing, hybrid geometric reconstruction, and validation procedures combining parametric, NURBS, mesh-based, and point-cloud-driven modelling approaches.

(iii) Information Mapping. Geometric entities are progressively enriched with semantic information, including historical documentation, material characterisation, conservation records, diagnostic investigations, and metadata, transforming geometric models into structured knowledge objects.

(iv) Information Sharing. Validated models are distributed through interoperable environments—including Common Data Environments (CDEs) and XR applications—to provide virtual access, management, communication, and dissemination while maintaining semantic consistency across digital platforms.

The entire framework is guided by six methodological principles: geometric accuracy, semantic consistency, data traceability, interoperability, scalability, and multidisciplinary integration. These principles govern the complete workflow, ensuring that information generated during each phase remains available and reusable throughout subsequent processes.

Validation is embedded throughout the methodology rather than being performed only at the end of the workflow. Each phase is assessed through dedicated criteria addressing dataset reliability, semantic consistency, interoperability, and information preservation,

ensuring that validated outputs become reliable inputs for subsequent stages. A defining feature of the proposed framework is the continuous exchange of information among specialised digital environments (Figure 1). Reality-capture datasets, geometric modelling, semantic enrichment, and information sharing are integrated through iterative interoperability pathways that preserve both geometry and associated information while supporting the progressive refinement of the digital ecosystem.

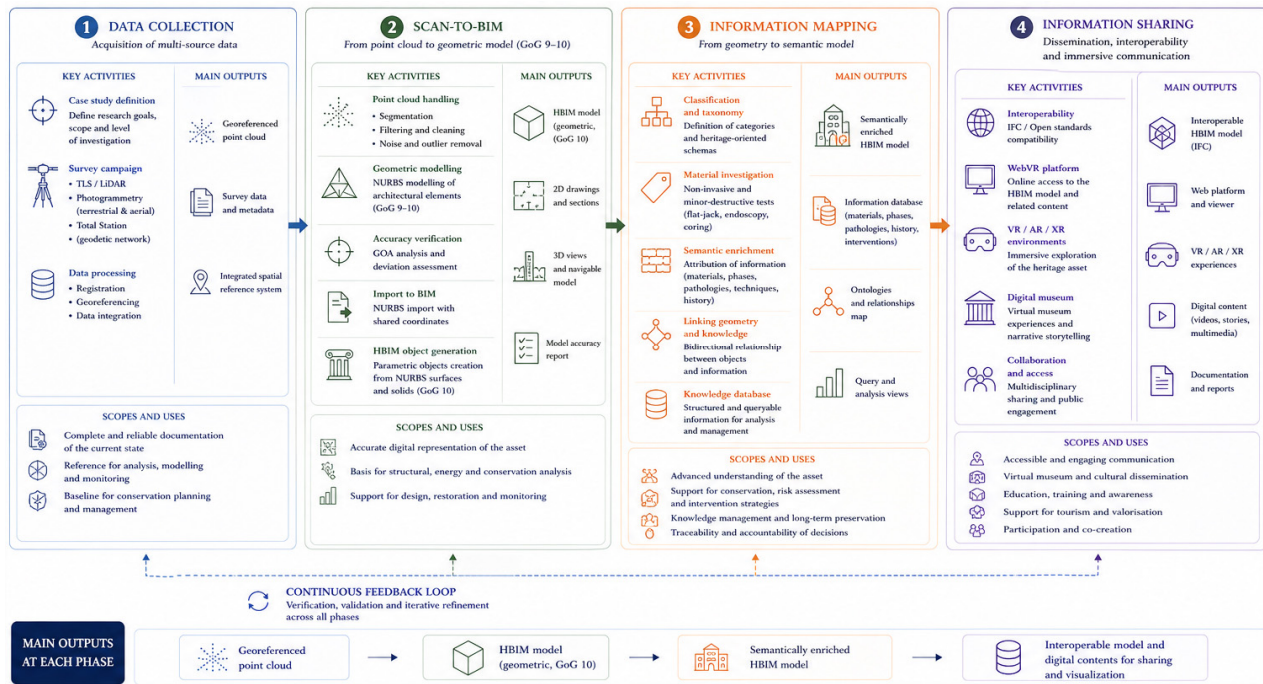


Figure 1. Ecosystem-based methodological framework proposed for the digitisation of CH. The diagram illustrates the continuous interaction between multi-scale reality capture, hybrid Scan-to-HBIM modelling, semantic information management, interoperability, and XR environments. Rather than representing a linear workflow, the framework supports the progressive generation, validation, exchange, and dissemination of geometric and semantic information throughout the heritage lifecycle.

2.2. Certosa di Pavia: An Experimental Testbed for an Ecosystem-Based Digital Framework

The Certosa di Pavia was selected as the experimental testbed for implementing and validating the proposed ecosystem-based framework. Its architectural scale, historical stratification, geometric complexity, and heterogeneous documentation provide an ideal environment for assessing an integrated digital workflow under real-world conditions. The coexistence of accessible and inaccessible spaces, multiple construction techniques, and multidisciplinary information sources require the coordinated integration of complementary survey technologies, modelling approaches, semantic structures, and interoperability strategies. From a methodological perspective, the Certosa concentrates within a single heritage asset many of the challenges that are typically addressed separately in CH digitisation, including multi-scale geometric acquisition, the representation of irregular architectural elements, the management of heterogeneous semantic information, the documentation of hidden spaces, and the long-term organisation of multidisciplinary datasets. These characteristics make the monument a suitable validation environment for assessing the applicability and robustness of the proposed framework (Figure 2).



Figure 2. UAV aerial views of the Certosa di Pavia. The first image shows a north-east view aligned with the main entrance and the church's principal axis, while the second presents a south-west view illustrating the spatial relationships among the church, the Ducal Palace, the cloister system, and the surrounding landscape.

Founded in 1396 by Gian Galeazzo Visconti as both a Carthusian monastery and dynastic mausoleum, the Certosa evolved through more than six centuries of construction, transformation, and conservation activities [3,4].

Successive building campaigns generated a highly stratified architectural system in which Gothic and Renaissance structures coexist with later additions, structural modifications, and restoration interventions.

This long-term evolution also produced an extensive body of historical, diagnostic, and technical documentation that forms an essential component of the monument's digital knowledge base. Architecturally, the complex comprises churches, cloisters, residential buildings, service areas, agricultural spaces, underground structures, roof systems, and technical infrastructures distributed across multiple spatial and functional scales (Figures 3–5). The coexistence of monumental architecture, richly decorated surfaces, irregular vaulted systems, stratified masonry, and extensive circulation networks requires acquisition and modelling strategies capable of adapting to different geometric and semantic conditions while maintaining a common spatial reference framework.



Figure 3. Main façade of the Certosa di Pavia. The image highlights the complex articulation of the polychrome marble surface, structured through horizontal registers and vertical partitions defined by pilasters, niches, and sculptural elements.

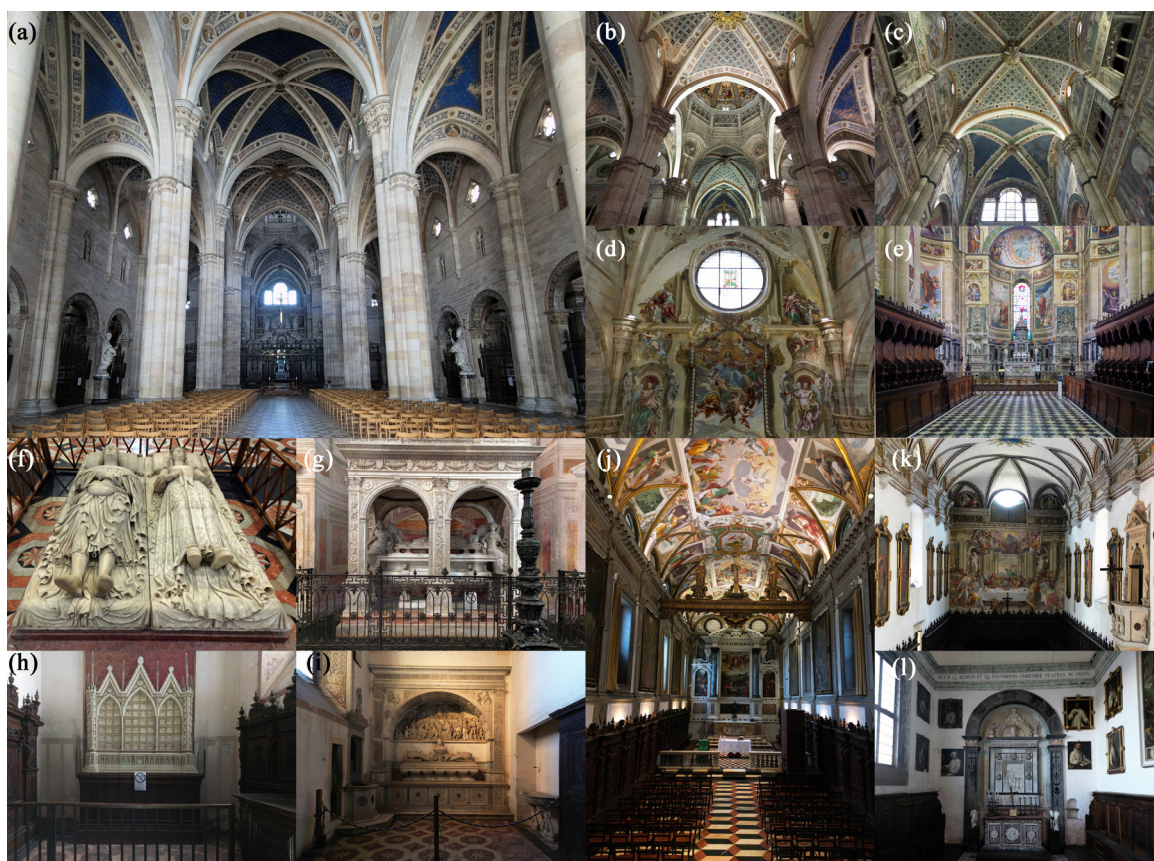


Figure 4. Interior spaces of the Certosa di Pavia. The images illustrate the spatial and functional organization of the monastic complex, highlighting the main church with its nave (a), tibrium (b), ribbed vault system (c), decorated transept (d), and choir (e). The liturgical and commemorative significance of the church is exemplified by the funerary monuments of Ludovico il Moro (f) and Gian Galeazzo Visconti (g). Additional views depict the Trittico degli Embriachi (h) and the lavabo (i) of the sacristies, the New Sacristy (j), the monumental refectory (k), and the chapter house (l), underscoring the close relationship between liturgical, communal, and functional spaces within the architectural structure of the Certosa.



Figure 5. Cloister system of the Certosa di Pavia. The upper-left image shows the small cloister (a), which organizes the monastery's principal communal spaces. The upper-right image illustrates the large cloister (b), arranged around the monks' cells and associated with the complex's eremitic dimension. The lower-left image depicts the cloister of Sant'Anna (c), linked to secondary and service functions (d). The remaining views show the woodyard cloister (e), the kitchen cloister (f), and the chapter spaces (g), highlighting the organization of functional and productive areas within the monastic system.

The monumental façade exemplifies the geometric and semantic complexity of the decorative heritage through its articulated system of marble inlays, sculptural elements, niches, and decorative partitions, while the interior spaces combine structural systems, decorative apparatuses, liturgical functions, and commemorative elements within highly complex volumetric configurations (Figure 3).

Internally, the Certosa is organised through a hierarchical sequence of liturgical, communal, and functional spaces. The church follows a Latin cross plan and preserves key elements of Lombard Gothic architecture, including ribbed vaults, pointed arches, and a strong vertical articulation of space. As shown in Figure 4, the nave, transept, tiburio, choir, and presbytery form a coherent spatial system enriched by frescoes, sculptural decorations, funerary monuments, marble surfaces, and intarsia works.

The funerary monuments of Ludovico Sforza and Galeazzo Visconti further emphasise the commemorative and political role of the church, reinforcing its function as a dynastic mausoleum conceived to celebrate the legitimacy, power, and cultural patronage of the ruling families of Milan. Beyond their historical significance, these sculptural ensembles represent masterpieces of Renaissance funerary art, characterised by complex iconographic programmes, refined decorative details, and a high degree of material and geometric complexity. Their coexistence with the architectural fabric contributes to the exceptional artistic and historical stratification of the Certosa, making the monument particularly

suitable for testing integrated multi-scale documentation, semantic modelling, and long-term digital preservation methodologies.

Adjacent spaces, including the New Sacristy, reinforce the continuity between liturgical and communal functions through complex volumetric and decorative configurations.

The relationship between the church and the cloister system defines the organisational core of the monastery, where circulation, ritual activities, and everyday life are structured through interconnected spatial sequences.

Similarly, the cloister system integrates communal, residential, productive, and service functions into a continuous architectural organism rather than a collection of isolated buildings (Figure 5).

Such characteristics pose significant methodological challenges for digital documentation. The coexistence of monumental architecture, highly decorated surfaces, irregular vaulted systems, stratified masonry, inaccessible environments, and extensive circulation networks requires flexible acquisition strategies capable of adapting survey resolution, modelling approaches, and semantic representation to diverse architectural conditions, while maintaining a consistent and shared spatial reference framework across the entire heritage site.

Likewise, the geometric variability of the monument cannot be adequately represented using conventional parametric BIM objects alone, as these are often unable to capture its irregularities and complex geometric features.

This requires the integration of complementary modelling paradigms—including parametric modelling, NURBS surfaces, mesh reconstruction, and direct point-cloud interpretation—according to the geometric and semantic characteristics of each architectural component. The small cloister organises the principal communal spaces of monastic life, including the chapter houses, refectory, and sacristies, while the large cloister—one of the largest in Europe—defines the eremitic dimension of the Carthusian order through the arrangement of autonomous monastic cells.

Each cell functioned as an autonomous living unit comprising residential rooms, workspaces, and private gardens, reflecting the balance between solitude and communal organisation typical of Carthusian monasticism. Additional cloisters connected to kitchens, storage areas, and service spaces further articulated the monastic system, forming an extensive network of functional and infrastructural environments.

Rather than isolated architectural episodes, these environments form a continuous and interconnected organism in which liturgical, residential, productive, and maintenance activities are spatially integrated. The internal organization of the Certosa extends beyond the monumental spaces typically accessible to visitors.

Beyond the monumental areas, the Certosa incorporates an extensive network of hidden and infrastructural environments—including attic systems, underground passages, service corridors, roof spaces, and technical infrastructures—that represent one of the principal methodological challenges addressed by the proposed survey strategy (Figure 6).

These spaces reveal the constructive and operational logic underlying the monument while providing essential information on structural behaviour, historical transformations, conservation conditions, and maintenance activities.

Unlike conventional documentation campaigns focused primarily on publicly accessible areas, the approach systematically includes these environments as integral components of digital representation, allowing the monument to be interpreted as a complete architectural system rather than as a collection of isolated monumental spaces.

These characteristics directly informed the design of the multi-scale survey strategy presented in the following section.

The integration of terrestrial laser scanning, UAV and close-range photogrammetry, topographic surveying, and georeferenced control networks was conceived as a unified acquisition process providing the geometric foundation for the subsequent modelling, semantic organisation, interoperability, and information-sharing phases.

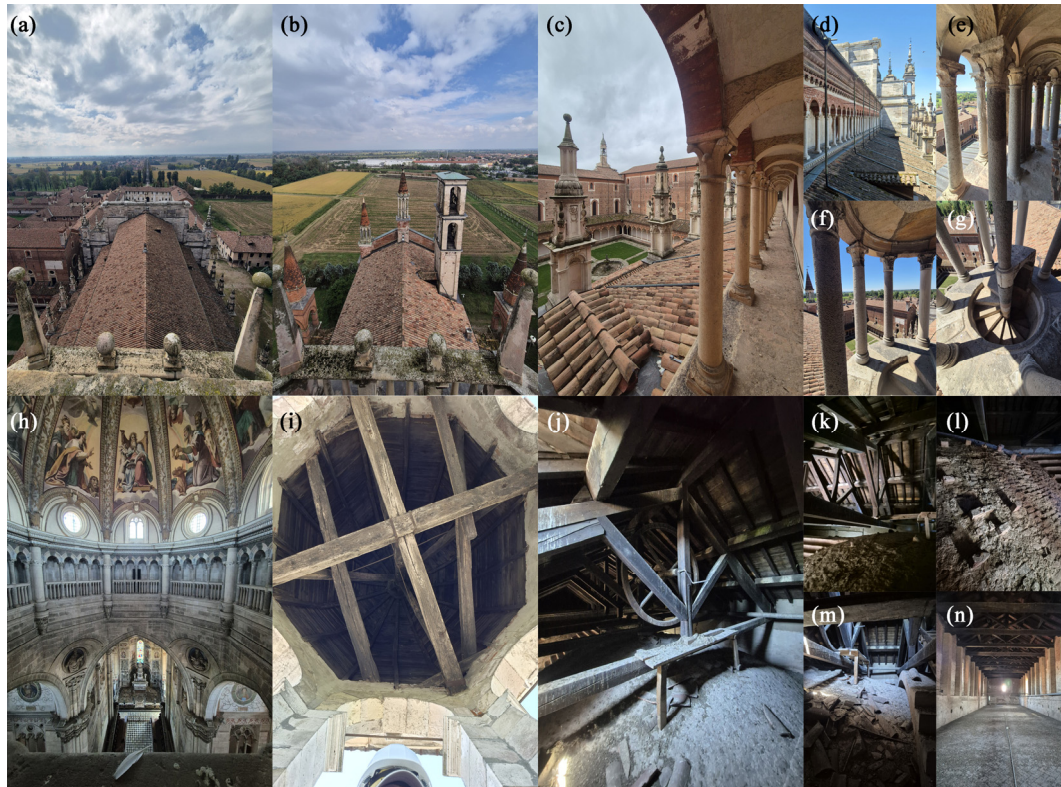


Figure 6. Interior and structural areas generally excluded from public access, highlighting the complexity of the monastic system beyond standard visitor routes. These include external ambulatory systems (a,b), service corridors (c), and attic spaces (d–g) above the church vaults, revealing internal circulation paths (h), roofing construction techniques (i–n), and the hidden infrastructural network supporting the liturgical, communal, and maintenance functions of the Certosa.

2.3. An Extensive Multi-Scalar Survey of the Certosa di Pavia: Data Acquisition and Processing

The data acquisition phase constitutes the first operational component of the proposed ecosystem-based framework by establishing the geometric reference for all subsequent modelling, semantic organisation, interoperability, and XR applications.

To ensure geometric consistency throughout the workflow, topographic surveying, TLS, and multi-scale photogrammetry were integrated within a coordinated acquisition strategy rather than applied as independent survey techniques.

The survey campaign combined complementary acquisition methods capable of adapting to different spatial scales, accessibility conditions, and levels of detail while maintaining a common geospatial reference framework.

This integrated approach provided the geometric basis for the subsequent Scan-to-HBIM workflow.

The survey campaign combined topographic measurements, terrestrial laser scanning, UAV and close-range photogrammetry within a coordinated workflow capable of adapting to different acquisition scales, accessibility conditions, and LODs while preserving spatial consistency across heterogeneous datasets.

The objective of the topographic survey was to establish a common geospatial reference framework capable of ensuring geometric consistency and interoperability among all

subsequent datasets. A rigorous topographic control network was established as the reference structure for the entire acquisition process (Figure 7).



Figure 7. Topographic survey operations at the Certosa di Pavia: (a) nave; (b) main entrance of the church; (c) Small Cloister—survey carried out using a Leica TPS1203 total station; (d) church forecourt—GNSS RTK survey conducted using an Emlid Reach RS3 receiver.

Beyond its georeferencing function, the network provides the common spatial infrastructure that ensures geometric consistency and interoperability among all datasets generated throughout the proposed digital ecosystem.

The topographic survey established the common spatial reference system supporting the integration of all subsequent datasets. A redundant control network, validated through least-squares adjustment and GNSS observations, ensured the geometric consistency required for TLS registration, photogrammetric orientation, and multi-source data integration.

The topographic control network covered the entire Certosa complex (approximately 300×300 m) and consisted of 31 interconnected survey stations uniformly distributed throughout the study area. The network was designed with redundant distance and angular observations to maximise geometric reliability during least-squares adjustment.

A total of 220 spherical and checkerboard targets were measured from the control network and subsequently used for the georeferencing of terrestrial laser scans and photogrammetric datasets. The adjusted network was computed through rigorous least-squares compensation, providing millimetre-level positional uncertainties for the control stations. GNSS observations were performed on five topographic control stations together with fifteen ground checkerboard targets distributed across the site.

These observations established the transformation between the local reference system and the UTM WGS84 RDN2008 coordinate system and supported the georeferencing of the UAV photogrammetric survey used for the generation of the general orthophoto.

The principal characteristics of the reference framework are summarised in Table 1.

Building upon the validated topographic framework, terrestrial laser scanning generated the primary geometric reference dataset for the entire project.

The acquisition strategy was designed to achieve complete coverage of the monument—including inaccessible spaces, underground areas, roof systems, and architecturally complex environments—while minimising occlusions and preserving geometric consistency (Figure 8).

Table 1. Topographic control network and georeferencing framework adopted for the Certosa di Pavia. The table summarises the principal characteristics of the topographic reference system, the validation procedures, and its contribution to the proposed ecosystem-based Scan-to-HBIM workflow.

Parameter	Specification	Validation/Accuracy	Contribution to the Digital Ecosystem
Survey area	Approximately 300 × 300 m	Complete coverage of the monastic complex	Spatial reference for the entire survey campaign
Topographic control network	31 measurement stations	Least-squares network adjustment	Common geometric framework for all datasets
Network configuration	Redundant reticular network	High observation redundancy	Maximises geometric reliability and spatial consistency
Total station	Leica TPS1203	Distance accuracy ± (2 + 2 ppm) mm; sub-milligon angular precision	High-precision topographic measurements
Topographic targets	≈220 checkerboard and spherical targets	Target residual analysis	Registration of TLS and photogrammetric datasets
Local reference system	Origin at Station 100; Y-axis aligned with the church	Millimetric internal consistency	Common reference for architectural documentation
GNSS receiver	EMLID Reach RS3 (RTK)	Centimetric positioning accuracy	Georeferencing of the survey network
GNSS service	SPIN3 RTK	Connection to the national reference system	Integration with geospatial datasets
Reference system	UTM WGS84 RDN2008	Verified through RTK observations	National geospatial compatibility
Geoid model	ITALGEO2005	Orthometric height transformation	Altimetric consistency
GNSS control stations	5	RTK verification	Georeferencing of the local network
Ground Control Points (GCPs)	15	Photogrammetric validation	UAV orientation and orthophoto accuracy
Orthophoto reference	1:500	Georeferenced product	Cartographic and planning reference
Integrated reference framework	Topographic network + GNSS	Millimetric (network); centimetric (GNSS)	Geometric backbone supporting TLS, photogrammetry, Scan-to-HBIM modelling, semantic information management, and XR applications

More than 1500 scans, corresponding to approximately 50 billion points, were acquired across the entire Certosa complex. Beyond producing the reference dataset for the subsequent Scan-to-HBIM process, the survey systematically documented architectural relationships that had never previously been recorded, revealing hidden circulation systems, roof voids, underground spaces, and wall thicknesses that now support conservation, structural assessment, and future restoration activities (Figure 9).

Point-cloud registration combined topographically measured targets with cloud-to-cloud refinement in Leica Cyclone REGISTER 360. Following geometric validation, the unified point cloud became the reference dataset for all subsequent modelling activities.

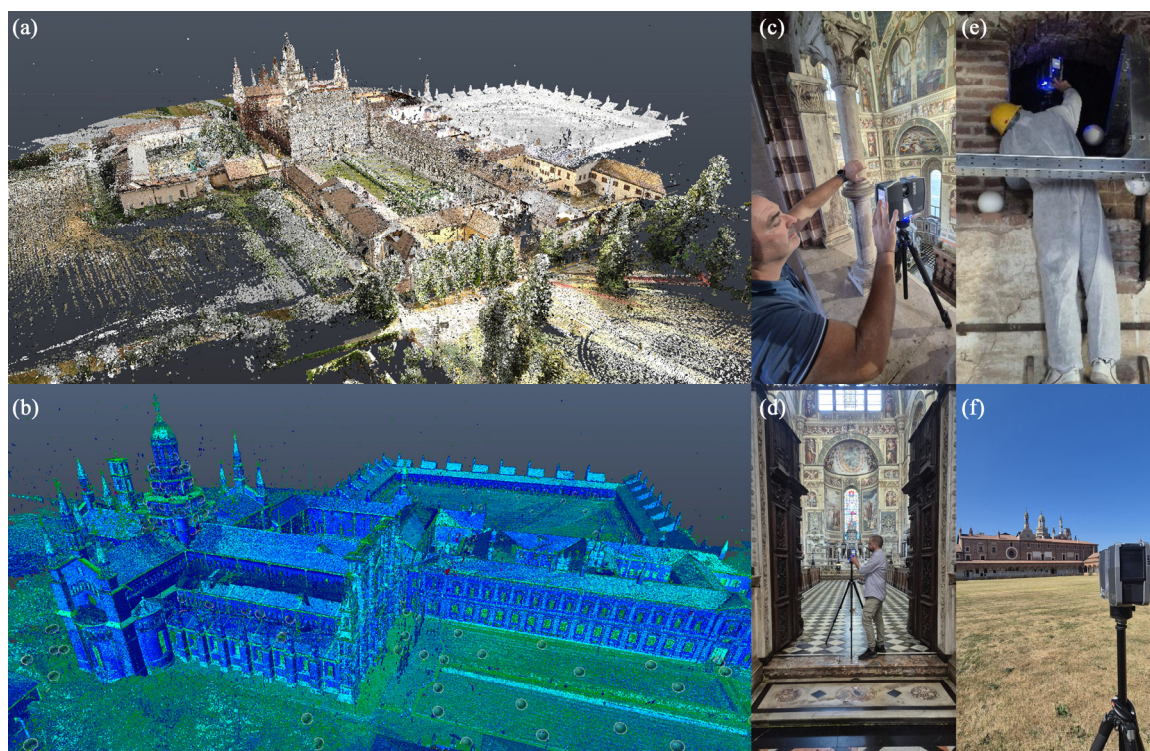


Figure 8. Terrestrial laser scanning (TLS) survey performed with a FARO Focus 3D X130 HDR to achieve comprehensive coverage of the entire monastic complex. (a) Overall survey of the Certosa di Pavia; (b) survey of the church and the Ducal Palace; (c) elevated galleries and loggias serving as circulation passages; (d) the choir; (e) the roof spaces and attics; (f) the Great Cloister.

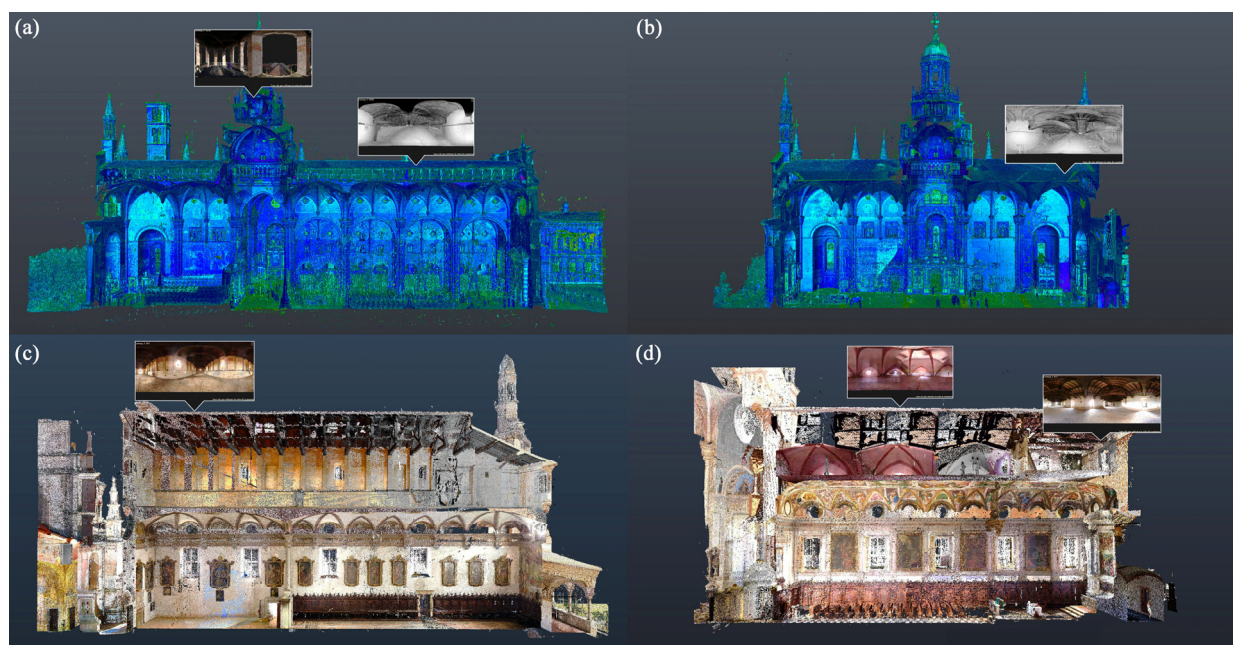


Figure 9. The main architectural volumes and their vertical spatial relationships: the church and its roof spaces (a,b), the New Sacristy (c) and the monumental refectory (d). Thanks to the survey activities, it was possible to reveal previously undocumented connections between these spaces, identify wall thicknesses, and, for the first time, document the buildings' existing conditions. The point clouds can be visualized using different display modes, such as intensity (a,b) and RGB values (c,d).

All laser scans were georeferenced using the checkerboard targets measured within the topographic network. The targets were distributed throughout the interior and exterior areas of the complex to ensure the registration of all survey sectors within a common geospatial reference framework. The average registration accuracy obtained during the georeferencing process ranged between 4 and 6 mm.

The principal acquisition parameters and validation metrics are reported in Table 2.

Table 2. Terrestrial laser scanning (TLS) acquisition and validation strategy adopted for the Certosa di Pavia: summary of the terrestrial laser scanning (TLS) campaign, registration strategy, and quality control procedures. The table synthesises the principal acquisition parameters and illustrates the contribution of the TLS dataset to the proposed Scan-to-HBIM, semantic modelling, and XR-oriented digital ecosystem.

Parameter	Specification	Validation/Accuracy	Contribution to the Digital Ecosystem
TLS acquisition system	FARO Focus 3D X130 HDR	Distance accuracy ≈ 1.2 mm @ 10 m; ≈ 2.0 mm @ 25 m	Reality-based acquisition of complex architectural geometries
Maximum acquisition range	130 m	Manufacturer specifications	Large-scale documentation of the entire monastic complex
Survey campaign	>1500 laser scans	Complete spatial coverage	Multi-scale acquisition of interiors, exteriors, roofs, underground spaces, and service areas
Point cloud dataset	≈ 50 billion points	Multi-resolution dataset	Geometric reference for the complete Scan-to-HBIM workflow
Survey extent	$\approx 331,000$ m ² ; ≈ 2.5 km perimeter	Full architectural coverage	Documentation of the entire heritage system
Acquisition strategy	Redundant scan positions with optimised overlap	Reduction of occlusions and shadow areas	Complete geometric representation of complex architectural environments
Registration method	Target-based registration + cloud-to-cloud refinement	Leica Cyclone REGISTER 360	Accurate alignment of individual scans
Registration targets	≈ 220 spherical and checkerboard targets	Topographically measured targets	Integration with the topographic reference framework
Registration validation	Target residuals, cloud-overlap consistency, bundle-adjustment statistics	Mean registration error ≈ 4 mm	Verification of global geometric coherence
Spatial reference	Topographic control network + GNSS	Millimetric local accuracy; centimetric global accuracy	Ensures interoperability with photogrammetric datasets
Main outputs	Unified georeferenced point cloud	Geometrically validated dataset	Geometric basis for Scan-to-HBIM modelling, semantic information management, interoperability, and XR applications

Photogrammetry complemented the TLS acquisition by providing multi-resolution datasets supporting architectural documentation, conservation analyses, semantic enrichment, and the generation of metric products at different representation scales. While terrestrial laser scanning established the primary geometric reference for the Scan-to-HBIM workflow, photogrammetry contributed radiometric information, high-resolution textures,

and detailed surface documentation, enabling a more comprehensive representation of the monument.

To address the architectural complexity of the Certosa di Pavia, the photogrammetric survey was organised into four complementary levels of investigation rather than a single acquisition campaign. Each level addressed a specific documentation objective while maintaining geometric consistency and interoperability within the common geospatial reference framework established by the topographic and TLS surveys. The photogrammetric blocks were constrained using the same integrated control network, ensuring geometric consistency between TLS and photogrammetric datasets throughout the entire acquisition workflow. Independent checkpoints were not introduced because the integrated acquisition strategy was based on a single georeferenced topographic network supporting the registration of both TLS and photogrammetric datasets. Consequently, the geometric validation focused on the consistency of the unified reference framework and on the subsequent cloud-to-model verification. This hierarchical organisation allowed acquisition parameters, image networks, and processing workflows to be adapted according to the required scale of representation and the intended use of the resulting products:

- Level 1—Territorial documentation, providing a georeferenced overview of the entire monastic complex and establishing the spatial reference framework for landscape analysis, roof inspection, and masterplan development.
- Level 2—Architectural documentation, focusing on façades, cloisters, courtyards, and interior spaces through the integration of UAV and terrestrial photogrammetry with TLS to support three-dimensional reconstruction.
- Level 3—Decorative documentation, dedicated to the high-resolution recording of artistic and architectural details for conservation, restoration, and material characterisation.
- Level 4—Metric documentation, integrating all validated datasets into orthophotos, plans, elevations, sections, and textured three-dimensional models supporting HBIM modelling and conservation activities.

The four levels should therefore be interpreted as complementary components of a single reality-capture strategy rather than as independent survey campaigns, collectively providing the geometric and radiometric foundation for the subsequent Scan-to-HBIM workflow. In particular, the first level focused on the territorial scale through UAV photogrammetry, producing a georeferenced orthophoto of the entire monastic complex together with roof documentation and architectural elements not visible from terrestrial surveys (Figure 10). This dataset established the common spatial reference for landscape analysis, architectural documentation, and subsequent HBIM activities. Each level addressed different scales of representation while maintaining consistency in metric reliability, coverage completeness, and interoperability between datasets. The objective was to generate a unified, georeferenced dataset that describes the site at both territorial and architectural scales and supports more detailed analyses.

This phase pursued three principal goals:

- to document structural elements not visible through terrestrial laser scanning, including roof systems, lanterns, upper cornices, and other inaccessible architectural components;
- to generate orthophotos of all elevations included within the survey programme;
- to produce a general orthophoto of the entire complex at a scale of 1:500.

Its geometric accuracy and radiometric consistency supported metric analyses, surface calculations, and spatial evaluations with a high degree of reliability. In particular, the orthophoto facilitated the assessment of built and open areas, the interpretation of circulation systems and landscape relationships, and the analysis of agricultural plots within the monastic precinct. During the initial phases of the masterplan definition, the

orthophoto also served as a reference layer for zoning studies, landscape evaluations, and the identification of functional and environmental relationships across the entire complex.

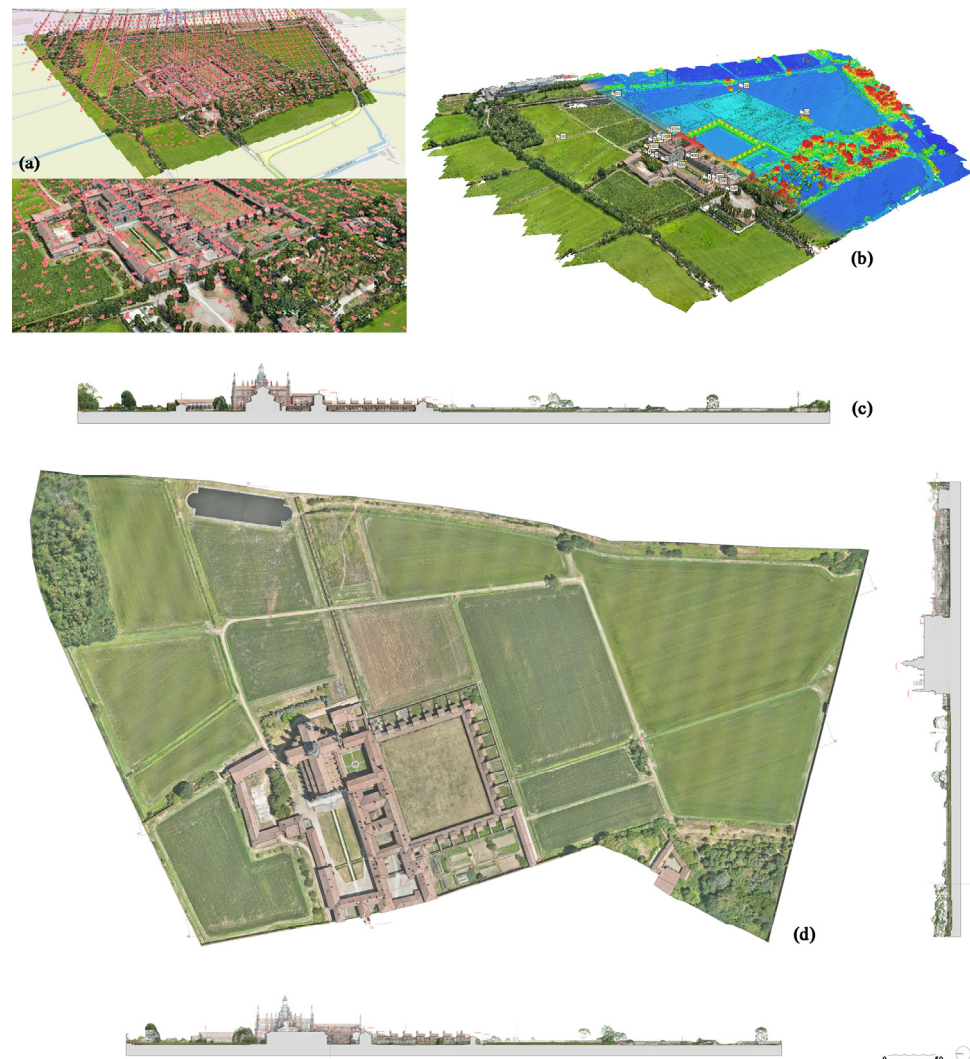


Figure 10. UAV photogrammetric survey of the entire complex. (a) UAV photogrammetry acquisition; (b) three-dimensional model of the entire complex, visualized using RGB values and a colour scale indicating elevation, from blue (lowest points) to red (highest points); (c) elevations and sections derived from the 3D model; (d) orthophoto of the entire complex at a scale of 1:500, with a ground sampling distance (GSD) of 2 cm, generated from the UAV photogrammetric survey.

From a conservation perspective, the orthophoto supported the preliminary identification of surface alterations, vegetation patterns, accessibility conditions, and spatial discontinuities, establishing a coherent basis for targeted diagnostic investigations and additional surveys. The availability of a unified and measurable visual framework also facilitated decision-making on intervention priorities, site accessibility, and the coordination of multidisciplinary design activities.

The second level focused on the detailed documentation of the architectural complex, including external façades, cloisters, courtyards, covered walkways, and historically significant interior spaces. This phase integrated terrestrial and low-altitude photogrammetry with terrestrial laser scanning to generate complete and coherent three-dimensional models (Figure 11).

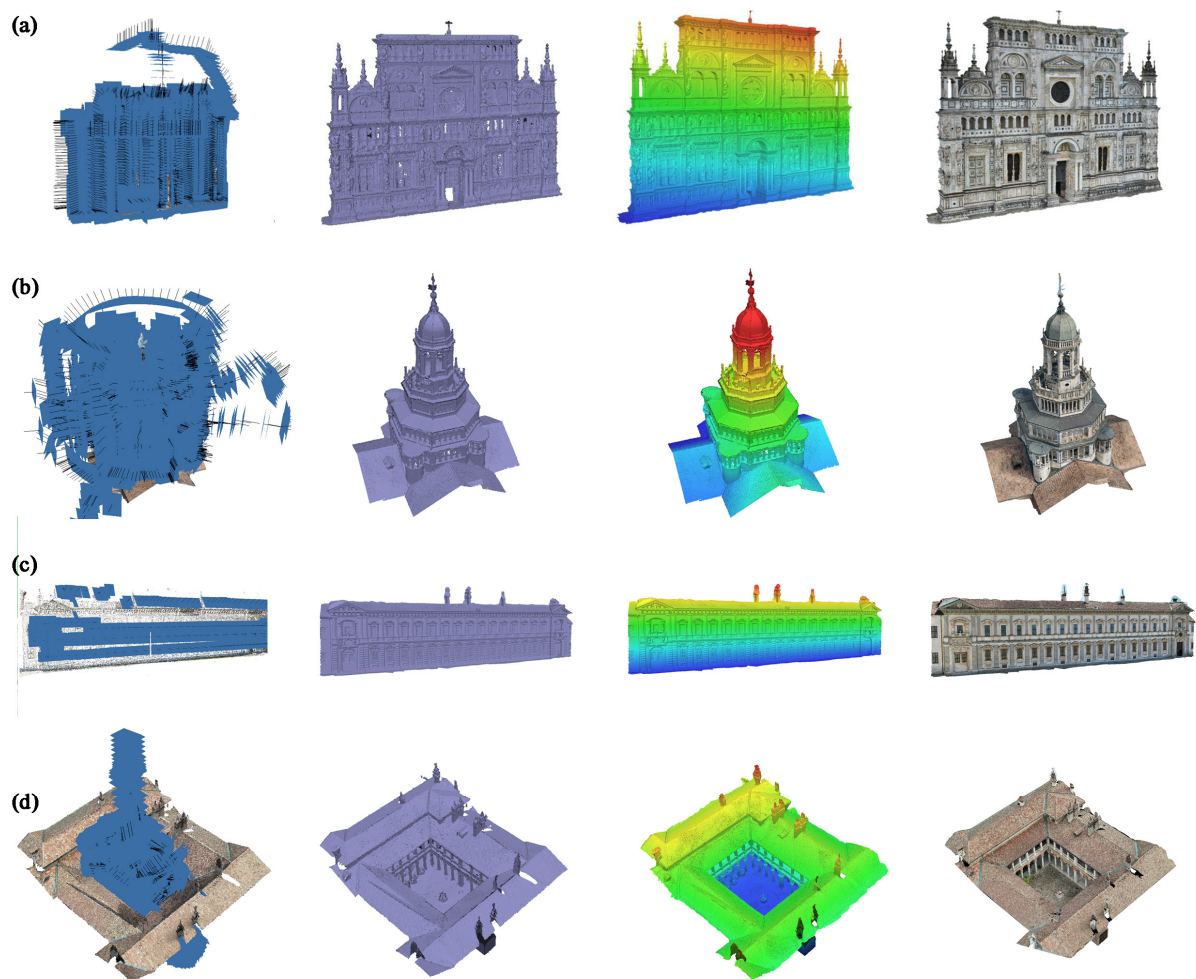


Figure 11. Photogrammetric workflow using a DJI Mavic Mini 3 Pro UAV, illustrated through selected projects—including the façade (a), the lantern (b), Palazzo Ducale (c), and the Cloister of Sant’Anna (d). The sequence shows dense point cloud generation (first column), mesh models (second column) models visualized using a colour scale indicating elevation, from blue (lowest points) to red (highest points) (third column), and textured meshes for producing high-resolution orthophotos of internal and external façades (fourth column).

More than 200,000 photographs were acquired using convergent multi-angular image networks to accurately reconstruct vertical surfaces and complex geometries while reducing occlusions. Particular attention was devoted to architecturally significant interior spaces, where tailored acquisition strategies ensured reliable photogrammetric reconstruction despite challenging lighting conditions.

The third level focused on the high-resolution documentation of artistic and decorative elements, including frescoes, sculptural apparatuses, architectural decorations, moldings, and ornamental details. The primary objective was to generate ultra-high-resolution orthophotos and textured three-dimensional models suitable for conservation, documentation, and restoration purposes (Figure 12).

Data acquisition was primarily conducted using a DJI Mini 3 Pro UAV, supplemented by close-range terrestrial photogrammetry as required. The main characteristics of the acquisition system are summarised in Table 3.

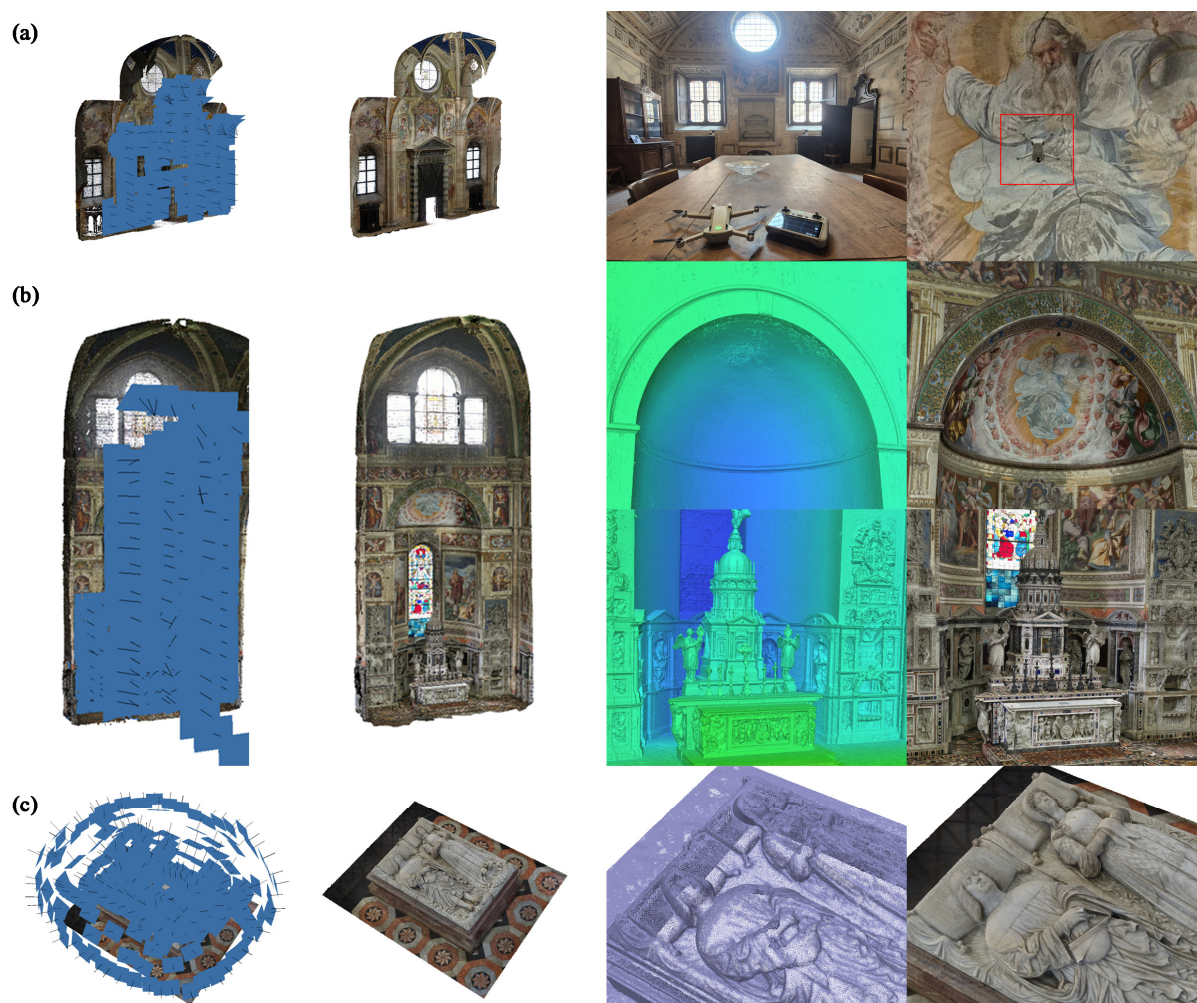


Figure 12. Photogrammetric workflow using a DJI Mavic 3 Pro UAV, illustrated through selected applications at the Certosa di Pavia: (a) the counter-façade, with the red box indicating the area where UAV acquisition was also performed for the internal portions of the complex; (b) the high altar in the apse area; and (c) the funerary monument of Ludovico il Moro and Beatrice d'Este. The workflow includes dense point cloud generation (first column), textured mesh reconstruction (second column), and high-detail representations of the architectural, decorative, and sculptural elements. The colour scale represents depth within the reconstructed models, with light blue indicating shallower areas and dark blue indicating greater depth or greater distance from the reference surface.

Table 3. Integrated multi-scale photogrammetric acquisition strategy adopted for the Certosa di Pavia.

Survey Level	Acquisition System	Main Outputs	Resolution/ Target Scale	Contribution to the Digital Ecosystem
Level 1—Territorial Survey	DJI Mavic 3E RTK UAV (20 MP CMOS)	Georeferenced orthophoto, dense point cloud	GSD $\approx$ 2 cm (1:500)	Establishes the territorial reference framework, supports georeferencing, masterplan development, landscape analysis, roof inspection, and integration with the topographic network.

Table 3. *Cont.*

Survey Level	Acquisition System	Main Outputs	Resolution/Target Scale	Contribution to the Digital Ecosystem
Level 2—Architectural Survey	UAV + terrestrial photogrammetry integrated with TLS	Dense point clouds, textured meshes, façade orthophotos	High-resolution architectural documentation	Supports the reconstruction of façades, cloisters, courtyards, interiors, and architecturally complex spaces within the Scan-to-HBIM workflow.
Level 3—Decorative Survey	DJI Mini 3 Pro UAV (48 MP) + close-range photogrammetry	Ultra-high-resolution orthophotos (GSD $\approx$ 0.6 mm), textured meshes	Sub-millimetric documentation	Supports conservation analyses, restoration, material mapping, semantic enrichment, and documentation of decorative elements.
Level 4—Integrated Documentation Products	Integrated TLS and photogrammetric datasets	Orthophotos, plans, elevations, sections, textured 3D models	Representation scales 1:20–1:100	Produces the metric documentation supporting HBIM modelling, restoration design, semantic information management, and XR applications.

The adopted workflow combined nadiral and oblique image configurations to generate convergent image networks that accurately reconstruct complex and difficult-to-access architectural elements, including lanterns, roof structures, decorated surfaces, and sculptural details.

The resulting photogrammetric products achieved an average pixel size of approximately 0.6 mm, enabling detailed analyses of material decay, surface discontinuities, chromatic variations, and micro-cracking, while providing reliable metric support for conservation and restoration activities.

The fourth level focused on integrating all acquired datasets into a coherent, scalable system primarily oriented toward producing orthophotos and architectural survey drawings. Photogrammetric acquisitions were specifically designed to support multiple output scales—1:20, 1:50, and 1:100 for detailed representations, ensuring consistency between metric accuracy and graphic restitution (Figure 13).

Particular emphasis was placed on generating orthophotos as primary metric support for the extraction of architectural drawings, including plans, elevations, and sections. These outputs enabled a rigorous and accurate graphical restitution of the surveyed elements, facilitating the interpretation of geometries, construction details, and stratigraphic relationships. The integration of aerial and terrestrial photogrammetry with laser scanning resulted in a comprehensive, continuous, and metrically reliable dataset. Photogrammetric products were verified against GCPs and the topographic reference network to ensure metric compatibility with the TLS dataset.

This multi-resolution system supports not only analytical and conservation-oriented activities but also the production of precise architectural documentation, forming a solid basis for restoration design and heritage management.

Consistent with the methodological principles introduced in Section 2.1, validation was integrated throughout the acquisition workflow rather than performed as a final verification stage. Each survey component was assessed using dedicated geometric and registration criteria before being incorporated into the subsequent Scan-to-HBIM process.

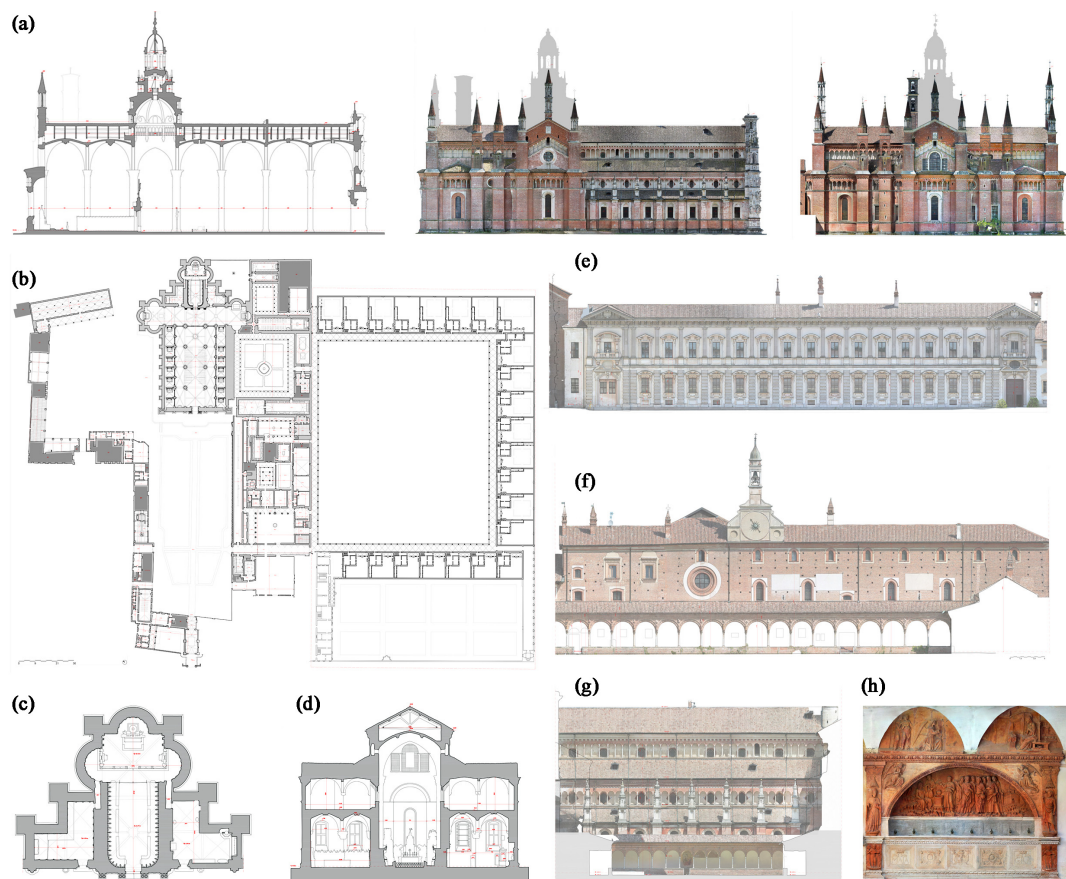


Figure 13. Orthophotos and CAD vector drawings for geometric architectural survey: upper—main section and elevations of the church (a); center left—ground floor plan (b); lower left—apse plan (c) and transverse section (d) with dimensions shown in red.; right—elevations of Palazzo Ducale (e), the main façade of the large cloister (f) and the small cloister (g); lower right—detail of the lavabo in the small cloister (h).

The topographic network was validated through least-squares adjustment and GNSS verification, ensuring the accuracy and consistency of the reference framework. TLS registration was assessed using target residuals, cloud-overlap consistency, and bundle-adjustment statistics to evaluate the quality of the point-cloud alignment.

Photogrammetric datasets were verified using GCPs and their geometric consistency with the topographic reference framework, ensuring reliable integration of the different survey datasets. These checks provided an independent assessment of the overall geometric reliability of the acquired data.

Finally, the geometric reliability of the Scan-to-HBIM reconstruction was assessed through point-to-surface deviation analyses between the HBIM models and the reference point clouds. The adopted validation procedures and quantitative results are summarised in Table 4.

Overall, the integrated acquisition strategy demonstrates that combining topographic surveying, terrestrial laser scanning, and multi-scale photogrammetry within a unified workflow provides a geometrically reliable and interoperable reference dataset for large-scale CH digitisation.

The validated reality-capture products constitute the geometric foundation of the proposed ecosystem, supporting the subsequent Scan-to-HBIM modelling, semantic information management, interoperability, and XR development phases.

Table 4. Validation framework adopted throughout the proposed ecosystem-based survey workflow.

Validated Component	Validation Procedure	Validation Metric	Result	Contribution to the Digital Ecosystem
Topographic control network	Least-squares adjustment of redundant observations	Coordinate residuals (σ)	Mean residuals: X = 4 mm; Y = 4 mm; Z = 2 mm	Establishes the geometric reference framework for all subsequent datasets
GNSS georeferencing	RTK verification against the national reference system	Positioning accuracy	Centimetric accuracy	Ensures consistency between the local and national coordinate systems
TLS registration	Target-based registration and cloud-to-cloud refinement (Leica Cyclone REGISTER 360)	Registration RMSE	Mean registration error (1230 scans): 4 mm	Validates the global geometric coherence of the point cloud dataset
TLS registration quality	Target residual analysis	Mean target residual	Mean residual: 3 mm	Verifies the reliability of scan alignment
Photogrammetric reconstruction	Ground Control Point (GCP) verification	GCP RMSE	East = 1.8 cm; North = 2.2 cm; Elevation = 3.5 cm	Validates georeferencing accuracy and geometric consistency
Integrated survey dataset	Comparison between TLS, photogrammetry, and topographic reference	Spatial consistency assessment	Consistent multi-source alignment	Confirms interoperability among heterogeneous datasets
HBIM geometric reconstruction	Cloud-to-model comparison	Point-to-surface deviation; RMSE	Results discussed in Section 3	Validates the geometric accuracy of the Scan-to-HBIM workflow
Digital ecosystem	Progressive verification throughout the workflow	Geometric consistency, semantic continuity, interoperability	Continuous validation process	Ensures the reliability of the complete ecosystem-based framework

3. HBIM as a Knowledge-Driven Digital Ecosystem: The Certosa di Pavia Case Study

The validated reality-capture datasets constitute the foundation for the hybrid Scan-to-HBIM strategy presented in this section. Within the proposed ecosystem, modelling is not limited to reconstructing architectural geometry but aims to preserve geometric reliability, semantic consistency, interoperability, and information continuity throughout the digital workflow. The following sections examine the proposed modelling strategy, the rationale behind the adoption of the Grades of Generation (GOG) framework, the validation of geometric reliability, and the organisation of semantic information and interoperability across the digital ecosystem.

3.1. HBIM Modelling Strategy and BIM Platform Comparison

The HBIM modelling phase represents the transition from validated reality-capture datasets to a structured knowledge environment. Within the proposed framework, modelling is conceived as a knowledge-generation process that progressively transforms geometric information into semantically enriched HBIM objects supporting conservation, management, interoperability, and long-term documentation. The objective therefore extends beyond producing geometrically accurate three-dimensional models. It requires preserving the relationship between geometric reliability, semantic information, and interoperability throughout the entire digital workflow. To identify the most appropriate modelling strategy, the principal BIM and geometry-based platforms currently adopted in CH applications were comparatively evaluated according to four methodological criteria:

- capability to represent irregular and historically stratified geometries;
- semantic information management and HBIM implementation;
- interoperability with external modelling, CDE, GIS, and XR environments;

- suitability for supporting the adopted GOG strategy.

The comparison revealed a persistent gap between BIM-oriented and geometry-based environments. BIM platforms provide advanced tools for semantic organisation, documentation, scheduling, and interoperability, but their parametric structure often limits the representation of irregular and non-standard geometries typical of historical architecture. Geometry-based environments, by contrast, allow greater flexibility in the modelling of complex morphologies through mesh- and NURBS-based approaches, although they generally lack native systems for structured information management and semantic organisation. The comparison included Autodesk Revit 2027 [69], Graphisoft Archicad 29 [70], ALLPLAN 2026 [71], ACCA Edificius 14 [72], Bentley OpenBuildings Designer [73], FreeCAD 1.1.1 [74], Rhinoceros 8 with Grasshopper [75], Blender 4.5 LTS [76], Autodesk 3ds Max 2027 [77], ZBrush 2026.2.1 [78], SketchUp 2026 [79], Autodesk Civil 3D 2027 [80], and Autodesk InfraWorks 2027 [81] (Figure 14). Rather than comparing commercial software, the assessment aimed to identify the role that each environment could perform within the proposed ecosystem.

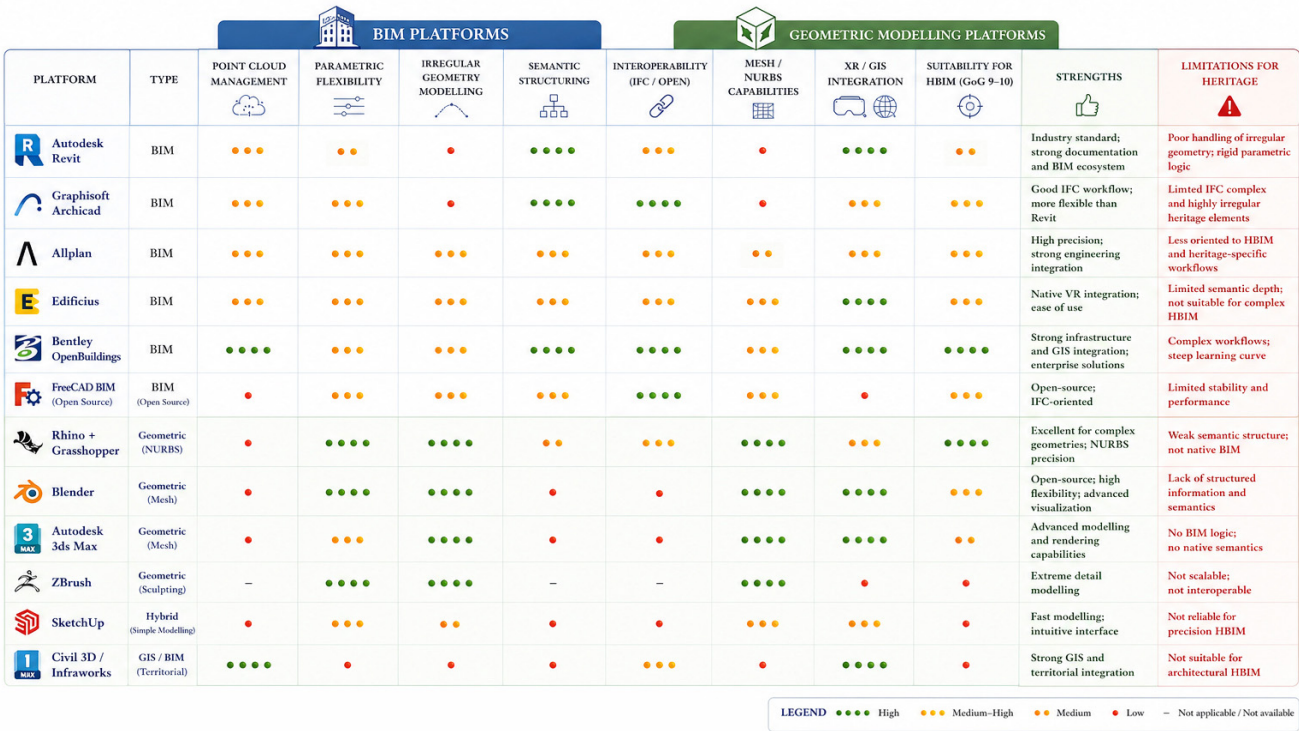


Figure 14. Comparative analysis of BIM and geometry-based modelling platforms adopted for HBIM applications. The comparison highlights the complementary capabilities of BIM and geometry-oriented environments, motivating the adoption of a hybrid Scan-to-HBIM strategy.

The comparison confirms that no single platform currently satisfies all the requirements associated with large-scale CH digitisation. BIM environments provide robust semantic organisation, documentation, and interoperability capabilities but remain constrained when representing irregular architectural geometries. Conversely, geometry-based platforms offer substantially greater flexibility for reconstructing complex morphologies through mesh- and NURBS-based modelling, while providing only limited support for structured semantic information. As a result, the present study adopts a hybrid modelling strategy in which specialised software environments operate as complementary rather than alternative tools. Within this workflow, Rhinoceros [76] supports NURBS- and mesh-based reconstruction of irregular geometries, whereas Autodesk Revit [70] provides the primary

HBIM environment for semantic enrichment and information management. Together, these platforms combine geometric flexibility with structured information management while maintaining interoperability throughout the modelling process. The resulting Scan-to-HBIM workflow is therefore conceived as an iterative process in which geometric reconstruction, semantic enrichment, validation, and interoperability evolve simultaneously, enabling the progressive transformation of validated point-cloud datasets into semantically structured HBIM models. The comparison presented in Figure 14 is not intended as a formal benchmark of commercial software platforms. Rather, it represents a methodological assessment developed during the implementation of the proposed workflow and supported by three complementary sources: (i) practical experience gained throughout the Certosa di Pavia project, including data processing, hybrid modelling, semantic enrichment, interoperability, and XR implementation; (ii) the capabilities and limitations documented in the current literature; and (iii) the authors' long-term professional experience in Heritage digitisation and HBIM-based workflows.

The evaluation criteria therefore reflect the ability of each software category to support the methodological requirements of the proposed ecosystem, including geometric modelling of irregular heritage elements, semantic information management, interoperability, and integration within the overall digital workflow. No weighted scoring system was applied, since the objective of the comparison is to clarify the complementary roles of different software environments rather than to rank individual platforms.

To overcome the limitations identified in the comparative assessment, the research adopts the GOG framework previously developed for HBIM applications [14,27].

Rather than defining different LODs, the GOG framework establishes progressive modelling strategies capable of integrating parametric, mesh-based, and NURBS-based reconstruction according to the geometric characteristics of each architectural component.

The GOG framework is organised into two principal groups (Figure 15):

- GOG 1–8, corresponding to modelling procedures natively implemented within BIM environments;
- GOG 9–10, based on advanced modelling approaches involving point cloud slicing, NURBS interpolation, and direct geometric generation from survey data.

The first eight grades are generally suitable for regular and standardised geometries, but they become less effective when applied to irregular, deformed, or highly articulated architectural elements. In these conditions, the extensive use of parametric families and boolean operations often results in inefficient and non-scalable workflows, particularly for large heritage models. For the Certosa di Pavia, GOG 9 and GOG 10 were systematically adopted in order to overcome these limitations.

Their relevance does not depend on modelling complexity alone, but on their capacity to combine geometric reliability, interpretative modelling, and interoperability within a coherent workflow.

GOG 9 is based on a slicing-oriented methodology in which point clouds are segmented into sections and transformed into a three-dimensional wireframe model. This wireframe, composed of boundary curves and internal sections, is subsequently interpolated into NURBS surfaces that can later be parameterised within BIM environments through tools such as “wall by face” or “roof by face” in Autodesk Revit [70].

The method enables the accurate reconstruction of complex geometries while maintaining control over the modelling logic and geometric interpretation. GOG 10 extends this approach by directly interpolating point clouds using advanced NURBS algorithms. In this case, intermediate sectional curves are replaced by control points distributed within closed boundaries, allowing surfaces to be generated more directly and then transferred into BIM environments.

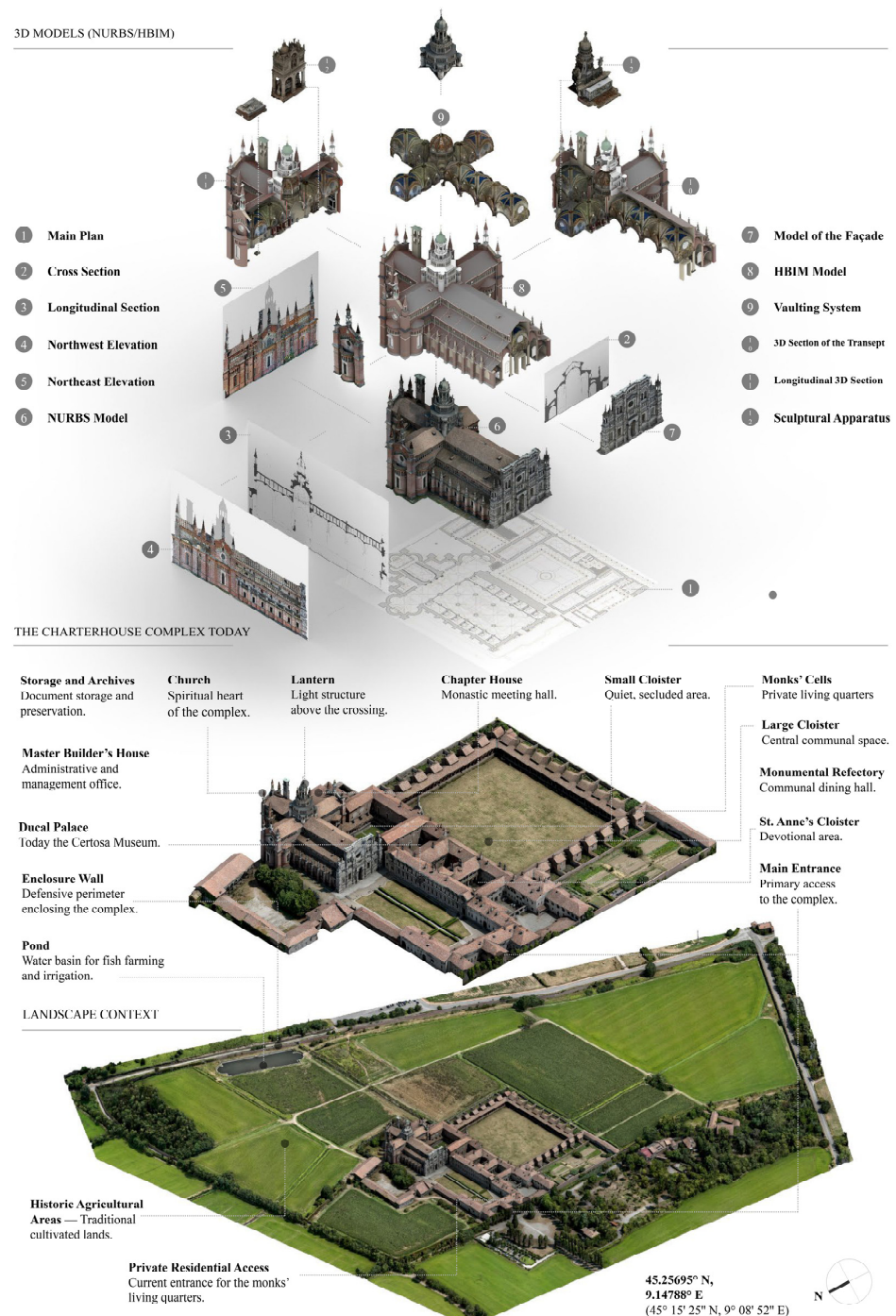


Figure 15. Multi-scale representation of the Certosa di Pavia, illustrating the transition from reality capture to NURBS reconstruction and HBIM implementation through the adopted GOG strategy.

Compared to more conventional, the adoption of GOG 9 and GOG 10 enabled the representation of highly irregular architectural components that could not be efficiently reconstructed using conventional parametric BIM objects alone. During the implementation of the Certosa di Pavia workflow, this hybrid modelling strategy proved operationally effective for managing complex geometries while maintaining the geometric accuracy validated through the cloud-to-model deviation analysis.

However, modelling time, labour effort, computational performance, and file-size reductions were not systematically recorded during the project. Consequently, any perceived improvements in modelling efficiency should be regarded as qualitative observations derived from practical implementation rather than experimentally validated results.

A central aspect of both GOG 9 and GOG 10 is the interpretative role of drawing within the modelling process. Rather than relying exclusively on automated procedures, the modeller actively selects, filters, and interprets point cloud information according to architectural and geometric criteria.

This process contributes not only to geometric accuracy, but also to the semantic consistency of the resulting HBIM models. Interoperability between Rhinoceros [76] and Autodesk Revit [70] was maintained through optimised exchange formats, enabling validated point clouds to remain the active geometric reference throughout the modelling process. Within this framework, BIM and geometry-based environments operate as complementary components of a continuous digital workflow rather than as isolated software platforms. Within the workflow, particular emphasis was placed on generating HBIM models directly from validated point-cloud data.

Unlike conventional parametric approaches, direct NURBS interpolation preserves the intrinsic morphology of irregular architectural elements, reducing modelling approximations and ensuring closer correspondence between the surveyed object and its digital representation.

This level of geometric reliability is fundamental for supporting subsequent applications, including architectural documentation, structural assessment, quantity take-offs, stratigraphic interpretation, and conservation analyses. Such a grade of accuracy (GOA) is essential to guarantee the scientific reliability of subsequent phases, including the production of architectural survey drawings (plans, sections, elevations), structural and stability analyses, the generation of HBIM schedules and inventories, quantity take-offs and cost estimation, the identification of stratigraphic units and the mapping and analysis of material decay and pathologies.

In this perspective, the adoption of GOG 9–10 is not only a modelling choice but a methodological requirement, as it establishes a direct and measurable relationship between the surveyed data and the resulting HBIM model, ensuring consistency across all downstream analytical and interpretative processes. This analysis provides a direct and measurable indicator of the geometric consistency between the survey data and the HBIM model.

The most suitable method for assessing the level of model reliability (LOR) was identified as the point-to-surface deviation analysis between the point cloud and the generated NURBS surfaces.

The following statistical parameters are considered:

Point count (n): total number of analysed points;

Mean distance (μ):

$$\mu = \frac{1}{n} \sum_{i=1}^n r_i$$

which should be close to zero to avoid systematic errors;

Median distance: a robust indicator used to detect outliers and gross errors;

Standard deviation (σ):

$$\sigma = \sqrt{\frac{\sum (x_i - \mu)^2}{n - 1}}$$

where x_i represents the distance between each point and the surface.

This method enables both a quantitative evaluation and a visual assessment through colour-coded deviation maps, where significant discrepancies are immediately identifiable. This combined approach allows deviations to be interpreted spatially and quantitatively, facilitating the identification of localised modelling errors as well as broader geometric inconsistencies. The approach was implemented using the PointDeviation tool in Rhinoceros [76], enabling rapid, intuitive validation of complex geometries (Figure 16).

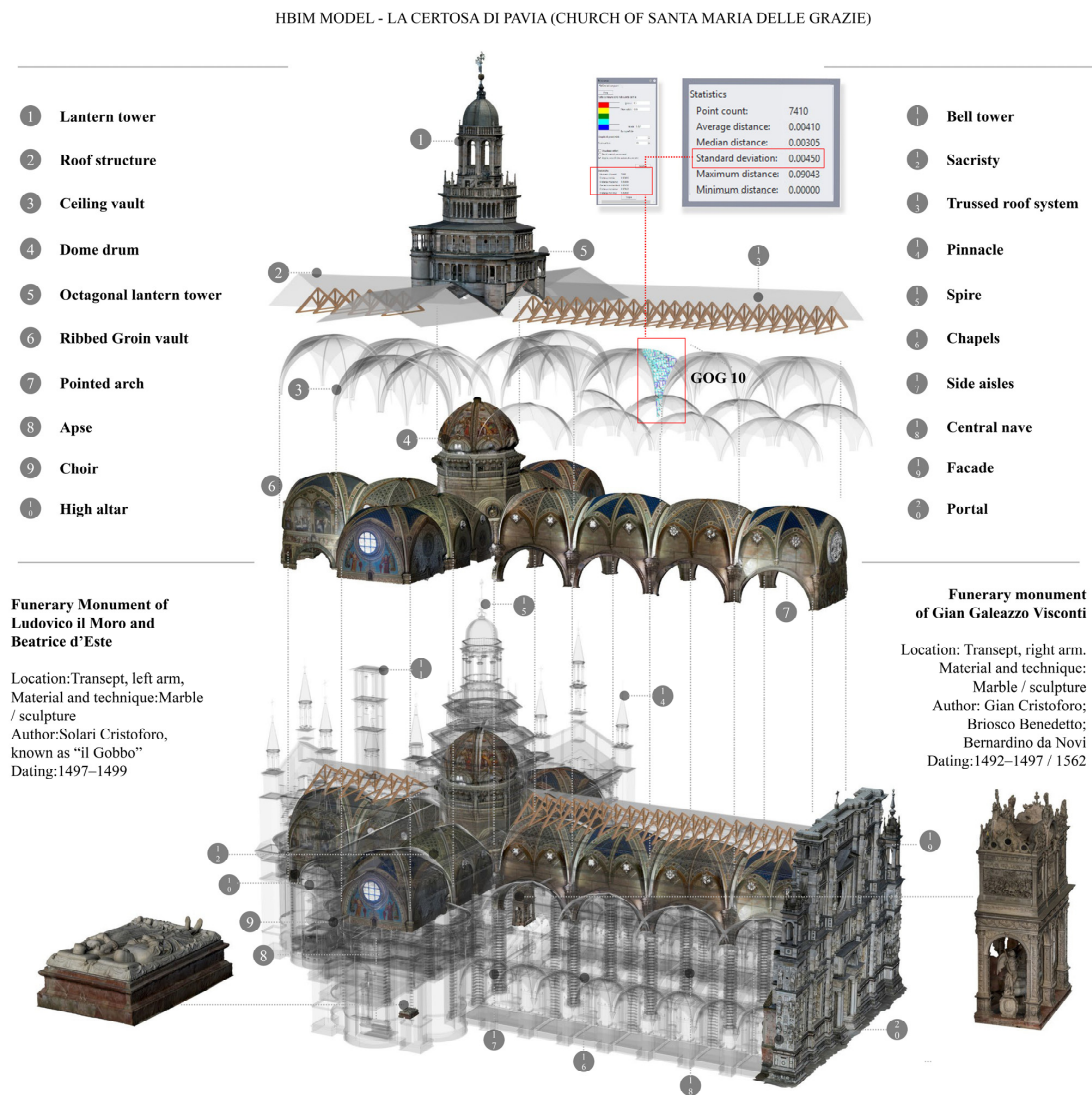


Figure 16. The HBIM model of the Certosa di Pavia consists of parametric BIM objects developed through different GOGs.

In this way, the comparison between the reference point clouds and the HBIM models can be performed directly within the modelling environment, reducing the need for additional software and simplifying the validation workflow.

The resulting deviation maps also provide a clear graphical representation that can be used to document the validation process and support subsequent modelling decisions.

The application of this method across multiple case studies demonstrated that optimising modelling procedures—particularly through GOG 9 and GOG 10—enables achieving a very high GOA, with deviations typically within the millimeter range. Furthermore, the method supports:

- automated analysis of highly detailed Scan-to-HBIM models;
- accessibility for non-expert users;
- efficient quality certification through numerical indicators;
- reduction of time and costs associated with validation procedures.

The integration of GOA assessment within the modelling workflow reinforces the reliability and scientific robustness of the proposed ecosystem, enabling continuous validation and improvement of HBIM models over time. This also makes it possible to identify critical areas at an early stage, supporting targeted corrections before the models are used

for subsequent analysis, documentation, or management activities. The iterative nature of this process further contributes to maintaining model accuracy as new information or more detailed surveys become available.

Together with the hybrid GOG modeling strategy and the interoperability-oriented workflow, this validation process demonstrates that the proposed digital ecosystem can support not only the production of highly accurate HBIM models but also their long-term management, semantic enrichment, and reuse across different CH contexts.

The proposed workflow therefore establishes a direct connection between geometric accuracy, modelling quality, and the broader requirements of digital heritage documentation and management.

Although the approach has been validated through the Certosa di Pavia, the workflow has been conceived as a transferable framework applicable to other large-scale, geometrically complex, and historically stratified CH sites. Its modular structure allows the validation procedures to be adapted to different levels of geometric complexity, data availability, and modelling requirements, while maintaining a consistent and measurable approach to quality assessment.

3.2. Validation of the Grade of Generation (GOG) Selection

Once the hybrid modelling strategy had been established, objective criteria were required to determine the most appropriate GOG for each architectural component. Rather than assigning GOGs according to predefined typological classes or operator experience, the workflow adopts a validation-driven decision process based on measurable geometric requirements.

The approach builds upon GOG framework originally introduced by Banfi [27] and its subsequent refinement through the integration of Grade of Accuracy (GOA) assessment and representation scales proposed by Brumana et al. [82]. Within the proposed workflow, the GOG is therefore interpreted as a methodological parameter rather than a modelling convention, ensuring that every modelling decision is supported by quantitative geometric validation.

The decision process begins by identifying the conceptual geometry that best approximates the surveyed architectural element (e.g., plane, prism, cylinder, cone, or sphere). The geometric deviation (ΔG) between this analytical reference and the validated point cloud is then quantified and compared with the admissible tolerance defined by the selected GOA and representation scale. The outcome determines whether the element can be reliably represented through conventional parametric BIM modelling or requires progressively more advanced reconstruction strategies.

When the measured deviation remains within the prescribed tolerance, conventional BIM modelling provides an adequate representation of the surveyed geometry, allowing the adoption of GOG 1–8 while preserving geometric reliability and semantic integrity. In particular, GOG 8 represents the highest level of native BIM modelling and was adopted whenever irregular components could still be reconstructed through parametric families and Boolean operations within Autodesk Revit [70].

When the measured deviation exceeds the admissible tolerance, simplified parametric modelling is no longer sufficient. Under these conditions, the workflow progressively shifts towards Advanced Modelling Techniques (AMT) based on NURBS reconstruction.

GOG 9 was adopted whenever irregular geometries could be reconstructed through section-based NURBS interpolation using wireframe models extracted from validated point clouds. Conversely, GOG 10 was selected for the most geometrically complex architectural elements—including barrel vaults, cloister vaults, rib vaults, domes, sculptural apparatuses, capitals, decorative elements, and highly deformed masonry surfaces—

where direct NURBS interpolation from point clouds was required to preserve the true architectural morphology.

The complete GOG selection process is summarised in Figure 17. By combining representation scale, GOA requirements, geometric deviation, and intended HBIM application, the proposed decision framework enables the systematic selection of the most appropriate modelling strategy while ensuring geometric reliability and methodological reproducibility.

ARCHITECTURAL ELEMENT	CONCEPTUAL GEOMETRY	REPRESENTATION SCALE	GOA	GOA TOLERANCE (max RMSE)	MEASURED DEVIATION (ΔG)	ADOPTED GOG	MODELLING STRATEGY	AUTOMATIC VALIDATION (AVS)	DECISION CRITERION
NATIVE BIM MODELLING (GoG 1–8)	Straight walls, floors, roofs	Plane	GOA100 GOA50	40–60 mm 20–30 mm	$\Delta G \leq T$	GoG 1–4	Parametric native modelling in Revit	Cloud-to-model verification	Conceptual geometry satisfies GOA
	Columns, pilasters	Cylinder / Prism	1:50	20–30 mm	$\Delta G \leq T$	GoG 1–7	Parametric native families	RMSE $\leq$ GOA	Parametric geometry sufficient
	Regular openings, niches, recesses	Plane + Boolean solids	1:20 – 1:50	8–30 mm	$\Delta G \leq T$ (after Boolean operations)	GoG 8	Void Families and Boolean subtraction from extracted profiles	Boolean verification + cloud comparison	Native BIM Boolean modelling preserves geometry and semantic relations
ADVANCED MODELLING TECHNIQUES – NURBS FROM PROFILES (GoG 9)	Arches	Circular / Polycentric curve	1:20	GOA20	$\Delta G > T$	GoG 9	NURBS reconstruction from sections and guide curves	RMSE + Mean deviation + σ	Profile-based modelling required
	Slightly deformed roofs	Free profile	1:20	GOA20	$\Delta G > T$	GoG 9	NURBS from extracted sections	AVS (RMSE + σ)	Simplified solids exceed GOA tolerance
	Slightly irregular masonry	Plane / Double plane	1:20	GOA20	$\Delta G > T$	GoG 9	NURBS surfaces from point cloud sections	RMSE + σ	Surface deformation requires NURBS modelling
ADVANCED MODELLING TECHNIQUES – DIRECT INTERPOLATION FROM POINT CLOUD (GoG 10)	Barrel vaults	Cylindrical surface	1:20 – 1:10	GOA20–10	$\Delta G > T$	GoG 10	Direct NURBS interpolation from point cloud	Full cloud-to-model analysis (RMSE, Mean, σ , AVS)	Deviation from conceptual solid exceeds GOA
	Cloister, cross, rib vaults	Intersecting surfaces	1:20 – 1:10	GOA20–10	$\Delta G > T$	GoG 10	Direct NURBS interpolation	AVS	Double-curvature geometry cannot be simplified
	Domes	Spherical / Elliptical surface	1:20 – 1:10	GOA20–10	$\Delta G > T$	GoG 10	Direct NURBS interpolation	Cloud-to-model validation	Conceptual solid exceeds GOA
	Star vaults, umbrella vaults, free-form vaults	Complex / Free geometry	1:20 – 1:10	GOA20–10	No conceptual solid satisfies GOA	GoG 10	Direct point-cloud interpolation	AVS + RMSE + Mean + σ	Direct modelling mandatory
	Sculptural apparatus	No conceptual primitive	1:10	GOA10	No conceptual primitive	GoG 10	Direct point-cloud interpolation	AVS	Free-form geometry
	Capitals, ornaments, decorative elements	No conceptual primitive	1:10	GOA10	No conceptual primitive	GoG 10	Direct NURBS from point cloud	Cloud validation	Maximum geometric fidelity
GOG DECISION RULE For each architectural element, the modelling strategy is selected according to the relationship between the required Grade of Accuracy (GOA), the adopted representation scale, and the measured geometric deviation (ΔG) between the surveyed point cloud and its corresponding conceptual geometric model. 1. $\Delta G \leq T(\text{GOA})$ → GoG 1–8 Native parametric BIM modelling 2. $\Delta G > T(\text{GOA})$ but geometry describable with sections/curves → GoG 9 NURBS reconstruction from sections and guide profiles 3. $\Delta G > T(\text{GOA})$ where $G_c = \{ \text{plane, cylinder, cone, sphere, ...} \}$ → GoG 10 Direct NURBS interpolation from point cloud 4. Cloud-to-model verification: RMSE $\leq$ GOA, Boolean verification, RMSE + Mean deviation + σ, AVS (Automatic Verification System), Full cloud-to-model analysis GOA – Expected Geometric Reliability (RMSE) GOA100 ≤ 40 mm GOA50 ≤ 20 mm GOA20 ≤ 8 mm GOA10 ≤ 4 mm									

T – admissible tolerance associated with the selected GOA and representation scale; AVS – Automatic Verification System; RMSE – Root Mean Square Error; σ – Standard Deviation; ΔG – Geometric Deviation

Figure 17. Validation-driven workflow for selecting the appropriate Grade of Generation (GOG).

The selected GOG was subsequently validated through quantitative GOA assessment based on point-to-surface deviation analysis between the generated NURBS models and the reference point clouds.

Unlike conventional visual inspection, this approach provides an objective evaluation of the correspondence between the surveyed geometry and the resulting HBIM model.

Validation was performed using the PointDeviation tool in Rhinoceros [76], which computes statistical descriptors together with colour-coded deviation maps that immediately identify local discrepancies between the model and the reference dataset.

The adopted assessment considers four complementary indicators:

- point count (n);
- mean deviation (μ), used to identify systematic modelling errors;
- median deviation, providing a robust indicator against local outliers;
- standard deviation (σ), adopted as the principal measure of geometric reliability.

Rather than representing a final quality-control procedure, GOA assessment is integrated within the modelling workflow, allowing modelling strategies to be iteratively refined until the required geometric reliability is achieved.

The application of this methodology demonstrated that GOG 9 and, particularly, GOG 10 enable millimetre-scale geometric accuracy while maintaining modelling efficiency and semantic consistency.

The quantitative validation presented in this study focuses exclusively on geometric reliability through cloud-to-model deviation analysis. No formal benchmark was performed to compare GOG 9–10 models with conventional parametric BIM objects in terms of modelling duration, computational requirements, file size, or resource consumption.

Such comparisons require controlled experimental conditions and systematic recording of modelling activities and are therefore identified as an important direction for future research. The cloud-to-model validation was performed on the principal architectural categories reconstructed throughout the Scan-to-HBIM workflow, including the complete vaulted systems and masonry partitions of the Certosa di Pavia together with representative decorative and sculptural components. Rather than being limited to a predefined numerical sample, the validation focused on the principal geometric typologies characterising the monument, thereby assessing the different modelling strategies adopted for both regular and highly irregular heritage geometries. Given the architectural scale and complexity of the monument, the validation was conceived as a typology-based assessment rather than an element-count-based comparison.

The resulting validation supports not only the generation of highly reliable HBIM models but also their subsequent use for architectural documentation, structural assessment, conservation analyses, quantity take-offs, and stratigraphic investigations. The quantitative results of the GOA assessment are presented in Figure 18 and discussed in the following sections.

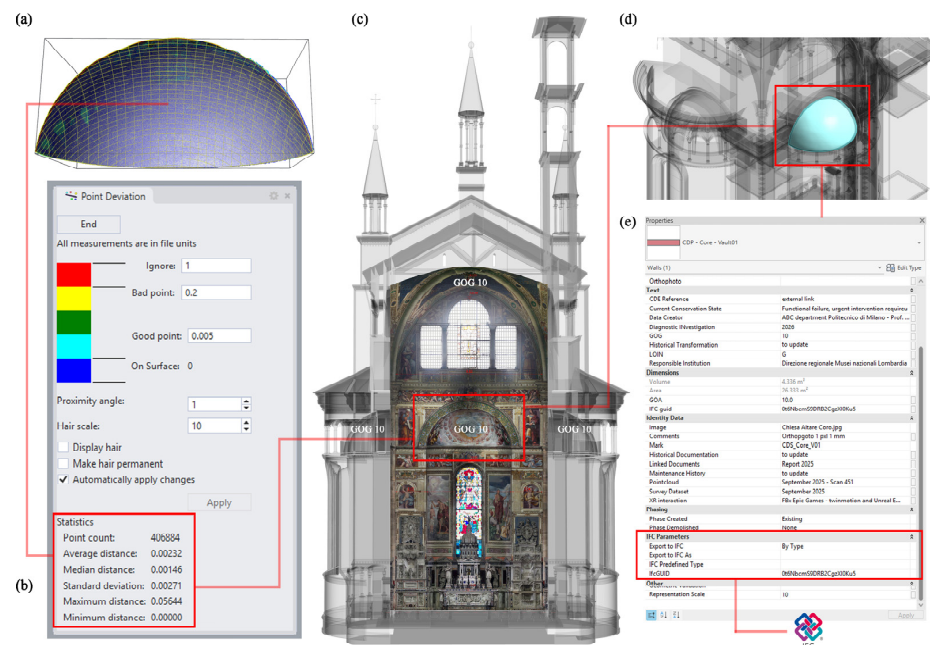


Figure 18. The semantic structure is based on hierarchical taxonomies and custom parameters compatible with IFC and openBIM principles rather than on a formally implemented semantic information structure. The workflow involves (a) the generation of the NURBS surface using GOG 10, (b) verification of its GOA, (c,d) conversion into a BIM object, and (e) the integration of additional information parameters prior to export in IFC format.

3.3. Semantic Information Management and Interoperability

After geometric validation, the approach progressively transforms validated HBIM models into semantically structured Knowledge Objects. Within the proposed framework, semantic modelling is not treated as a subsequent enrichment stage but as an integral component of the modelling process, linking validated geometry with historical documentation, material characterisation, diagnostic investigations, conservation records, maintenance information, and metadata. Each HBIM object therefore becomes a structured knowledge entity in which geometric reliability, historical identity, conservation status, and semantic information remain permanently associated throughout the digital workflow. Semantic information is assigned according to the required LOIN and the intended

application of each object, combining standard BIM parameters with custom attributes, relational databases, metadata schemas, and linked documentation in accordance with the ISO 19650 framework.

Beyond descriptive attributes, every HBIM object explicitly records the adopted GOG, GOA, representation scale, and the corresponding validation result. Thus, each object preserves not only its geometric representation but also the complete history of its generation, validation, semantic enrichment, and intended use throughout the heritage lifecycle. Because conventional BIM schemas rarely accommodate the geometric irregularities, historical stratification, and interpretative uncertainty characteristic of CH assets, the proposed framework adopts an extensible semantic structure based on hierarchical taxonomies, custom parameters, and interoperable classification systems while maintaining compatibility with IFC standards and openBIM principles.

The proposed semantic structure adopts hierarchical taxonomies and custom parameters compatible with IFC and openBIM principles. However, a formal semantic organisation was not implemented in the present study. Instead, the semantic framework relies on structured HBIM objects and interoperable information schemas specifically designed to support documentation, conservation, and information exchange.

The development of a dedicated CH semantic information structure capable of formalising semantic relationships between architectural components, historical phases, conservation records, and external knowledge repositories represents an important direction for future research. Within this perspective, geometric modelling and semantic organisation evolve simultaneously, allowing the HBIM model to operate as a dynamic knowledge environment rather than as a static three-dimensional representation.

A representative implementation of the proposed HBIM Knowledge Object is illustrated in Figure 18. Interoperability represents the mechanism through which the proposed framework preserves the relationships between geometry, semantic information, and heritage knowledge across the complete Scan-to-HBIM workflow. Rather than relying on isolated file conversions, validated datasets are exchanged among specialised modelling environments through coordinated interoperability pathways that preserve both geometric and semantic consistency. The semantic information intentionally preserved throughout the interoperability process includes object identifiers, typological classifications, descriptive metadata, historical documentation, conservation records, diagnostic information, material characterisation, and LOIN. These information categories constitute the semantic core required to support documentation, conservation, management, and dissemination across the different digital environments adopted in this research.

Within the proposed framework, interoperability operates simultaneously at three complementary levels:

- Geometric interoperability, preserving metric reliability and spatial consistency during data exchange between reality-capture datasets, geometry-based modelling platforms, and HBIM environments.
- Semantic interoperability, maintaining the relationships between HBIM Knowledge Objects, historical documentation, diagnostic information, conservation records, metadata, and LOIN.
- Functional interoperability, enabling the same validated information to be reused across multiple applications—including conservation, structural assessment, facility management, documentation, DTs, and XR environments—without interrupting the continuity of the digital workflow.

A central component of this infrastructure is the CDE, which provides coordinated information management, version control, collaborative access, and traceability throughout the workflow while ensuring synchronisation among modelling platforms, semantic repos-

itories, and downstream applications. Interoperability further extends towards immersive visualisation environments through dedicated exchange pathways connecting the HBIM model with Twinmotion and Unreal Engine. These environments preserve the relationship between geometry and semantic information while enabling DT development, virtual exploration, and XR-based dissemination. The complete interoperability framework is summarised in Figure 19, which illustrates the adopted software environments, exchange formats, and interoperability pathways connecting reality capture, geometric modelling, HBIM implementation, semantic information management, CDEs, and downstream XR applications. The proposed semantic organisation should therefore be understood as an application-specific information structure based on HBIM Knowledge Objects and interoperable metadata rather than as a formal ontology or ontology-based knowledge representation system.

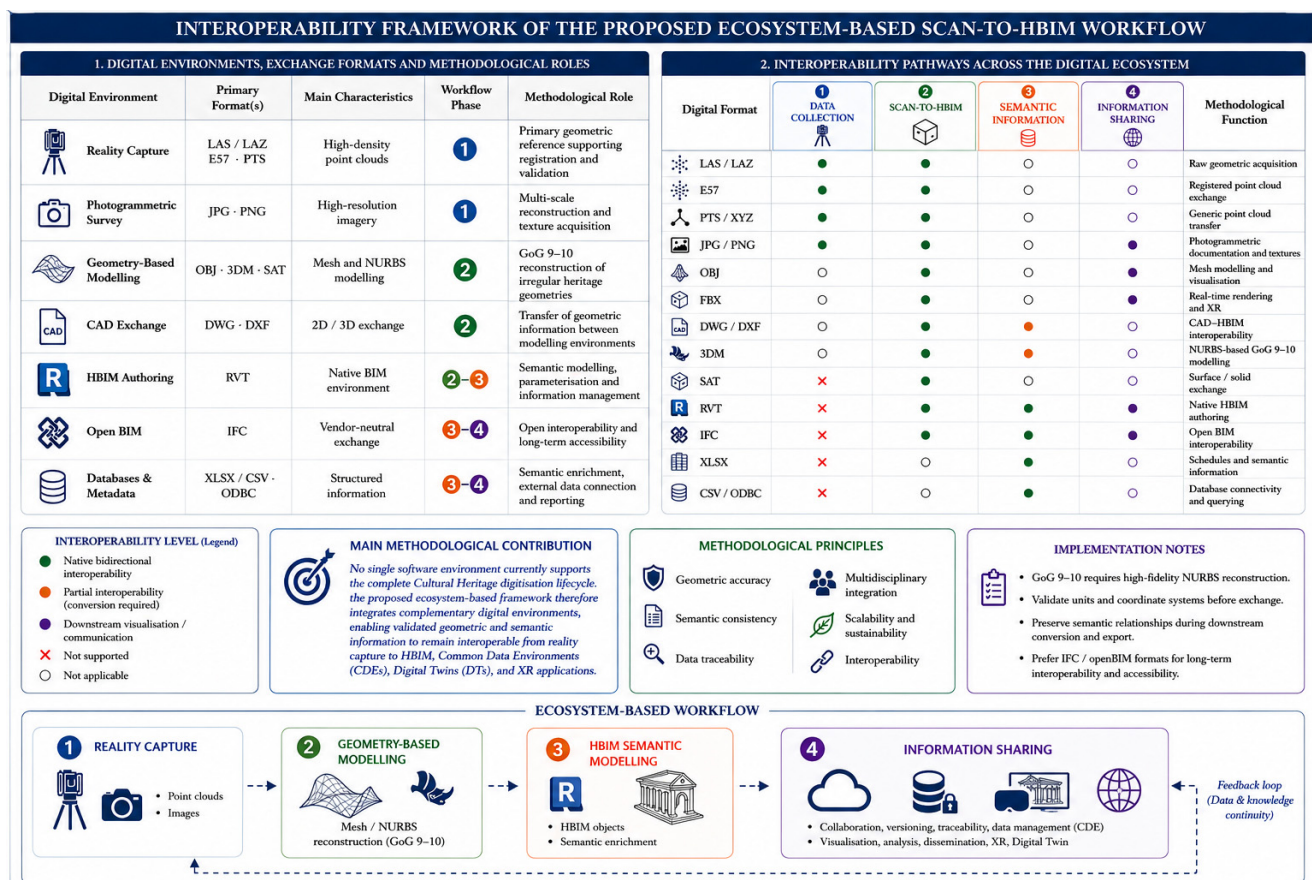


Figure 19. Interoperability framework adopted throughout the proposed Scan-to-HBIM workflow. The diagram summarises the principal exchange formats, software environments, and interoperability pathways supporting the continuous preservation of geometry, semantic information, and data traceability across the CH lifecycle.

4. Information Sharing: From HBIM to Extended Reality (VR-AR and WebXR), Serious Games and Virtual Museums

4.1. VR and WebXR Development Process for the Certosa di Pavia: Platforms, Environments, and Interoperability

The final stage of the proposed framework extends validated HBIM Knowledge Objects towards immersive information-sharing environments. Rather than considering XR as a standalone visualisation technology, the proposed method adopts it as the environment

through which validated heritage information becomes accessible for communication, interpretation, education, conservation, and public dissemination.

The objective is to transform validated HBIM models into interactive digital environments while preserving the relationships between geometry, semantic information, historical documentation, and conservation records established throughout the Scan-to-HBIM workflow. The same information structure therefore supports VR, WebXR, DT, and serious-game applications without requiring independent model reconstruction or duplicated information management. To identify the most suitable development strategy, the principal VR, AR, and WebXR platforms currently adopted in CH applications were comparatively evaluated according to six complementary criteria: degree of immersion, level of user interaction, interoperability with HBIM environments, flexibility for custom development, virtual access across desktop, mobile, and VR devices and suitability for information sharing and heritage dissemination. The assessment included real-time visualization platforms, namely Twinmotion 2026.1 [83] and Enscape 4.6 [84]; real-time development environments, including Unreal Engine 5.8 [85] and Unity 6.3 LTS [86]; and browser-based WebXR solutions, including Twinmotion Cloud [87], PlayCanvas Engine 2.20.6 [88], 8th Wall [89], and Babylon.js 9.8.0 [90] (Figure 20).

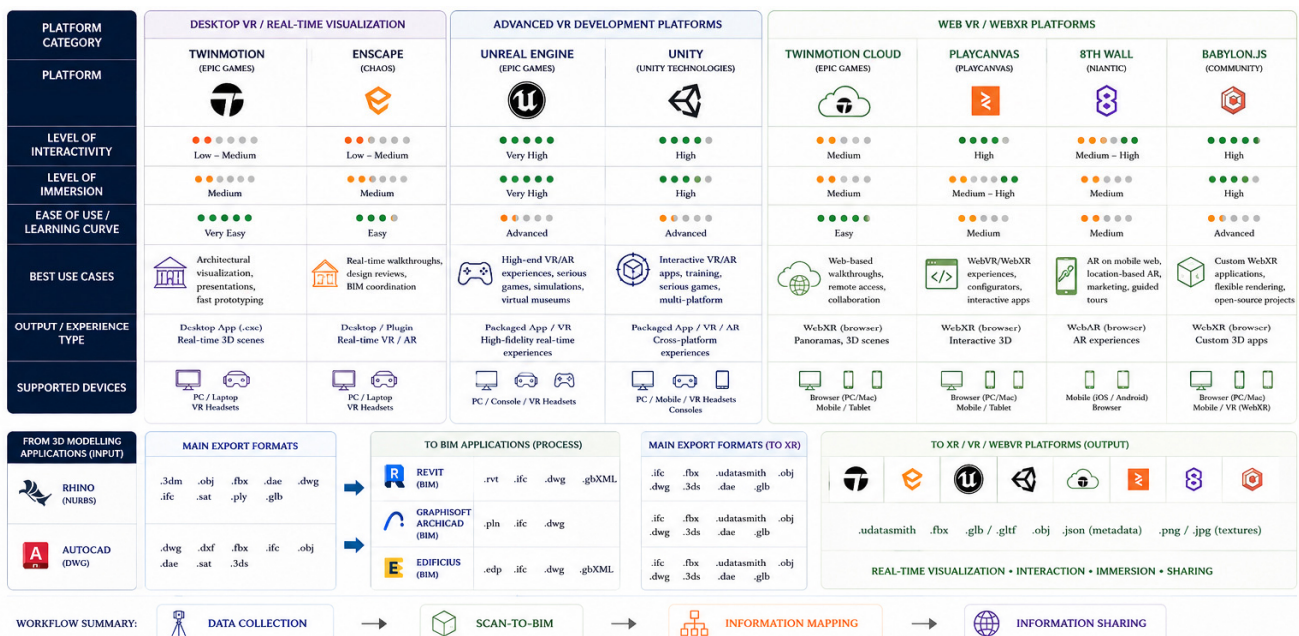


Figure 20. Comparative assessment of immersive development platforms adopted for the Information Sharing phase. The figure compares the principal XR environments according to immersion, interaction, accessibility, interoperability, and development flexibility while summarising the principal exchange formats connecting HBIM, geometry-based modelling, and XR applications.

The comparison highlights complementary rather than competing capabilities. Real-time visualisation platforms—particularly Twinmotion—support rapid environment generation and effective communication through streamlined workflows. Conversely, development environments such as Unreal Engine provide greater flexibility for interaction design, behavioural programming, and immersive experiences, although at the cost of increased development complexity.

Browser-based WebXR solutions offer the widest accessibility but currently present limitations when handling highly detailed HBIM-derived environments. Based on this assessment, the workflow adopts a hybrid XR workflow combining Twinmotion and Unreal Engine. Twinmotion supports rapid production of immersive environments for

communication and dissemination, while Unreal Engine extends these environments through advanced interaction, adaptive navigation, and customised user experiences.

A key component of this workflow is the adoption of Visual Programming Language (VPL) paradigms. Through the Unreal Engine Blueprint system, validated HBIM entities are progressively transformed into Interactive Virtual Objects (IVOs) by associating geometric elements with behaviours, events, and interaction logic derived directly from their semantic information.

4.2. Adaptive Virtual Experience for the Certosa di Pavia

The XR strategy was subsequently implemented through an adaptive information-sharing approach capable of generating multiple immersive experiences from the same validated HBIM dataset. Rather than producing static visualisation models, the workflow extends the Scan-to-HBIM process towards interactive environments supporting communication, interpretation, virtual access, and cultural dissemination.

The primary objective is to preserve the semantic structure established during the HBIM process while adapting the same digital assets to different immersive environments and user profiles. Accordingly, a single validated HBIM model supports multiple outputs—including real-time VR applications, ongoing WebXR developments, cinematic visualisations, future virtual museum environments, interactive museum installations, and DT environments—without requiring duplicated models or independent information management.

A fundamental aspect of the methodology is the preservation of semantic relationships throughout the HBIM-to-XR transformation. Geometric entities remain associated with their object identifiers, metadata, historical documentation, conservation records, and LOIN, allowing users to interact not only with three-dimensional geometry but also with the knowledge embedded within each architectural component.

Within the implemented XR environment (Figure 21), users can access selected semantic information associated with each HBIM Knowledge Object, including object identification, descriptive metadata, historical documentation, conservation records, and linked multimedia resources. The immersive applications are not intended to replicate the complete HBIM authoring environment but rather to provide structured access to validated information supporting interpretation, communication, and cultural dissemination.

The implemented workflow combines the complementary capabilities of Twinmotion and Unreal Engine. Twinmotion enables the rapid generation of immersive environments for communication, exhibition design, and public dissemination, whereas Unreal Engine extends these environments through adaptive navigation, event-driven interaction, and VPL (Blueprint) logic. Within this framework, validated HBIM entities evolve into IVOs capable of responding dynamically to user interaction while preserving the semantic information inherited from the HBIM model.

The transition from the HBIM environment to the XR applications was implemented through an integrated export workflow combining FBX and Datasmith. Parametric HBIM models developed in Autodesk Revit [70] together with NURBS-based models generated in Rhinoceros were exported as FBX datasets and synchronised with the real-time visualisation environment using Datasmith, ensuring the preservation of the geometric hierarchy, object organisation, materials, and scene structure throughout the conversion process.

Model optimisation was selectively applied according to the geometric complexity and visual importance of each architectural component. Mesh decimation procedures were primarily performed on highly detailed decorative elements—including sculptures, bas-reliefs, and ornamental components—while the architectural geometry of the HBIM models remained substantially unchanged.

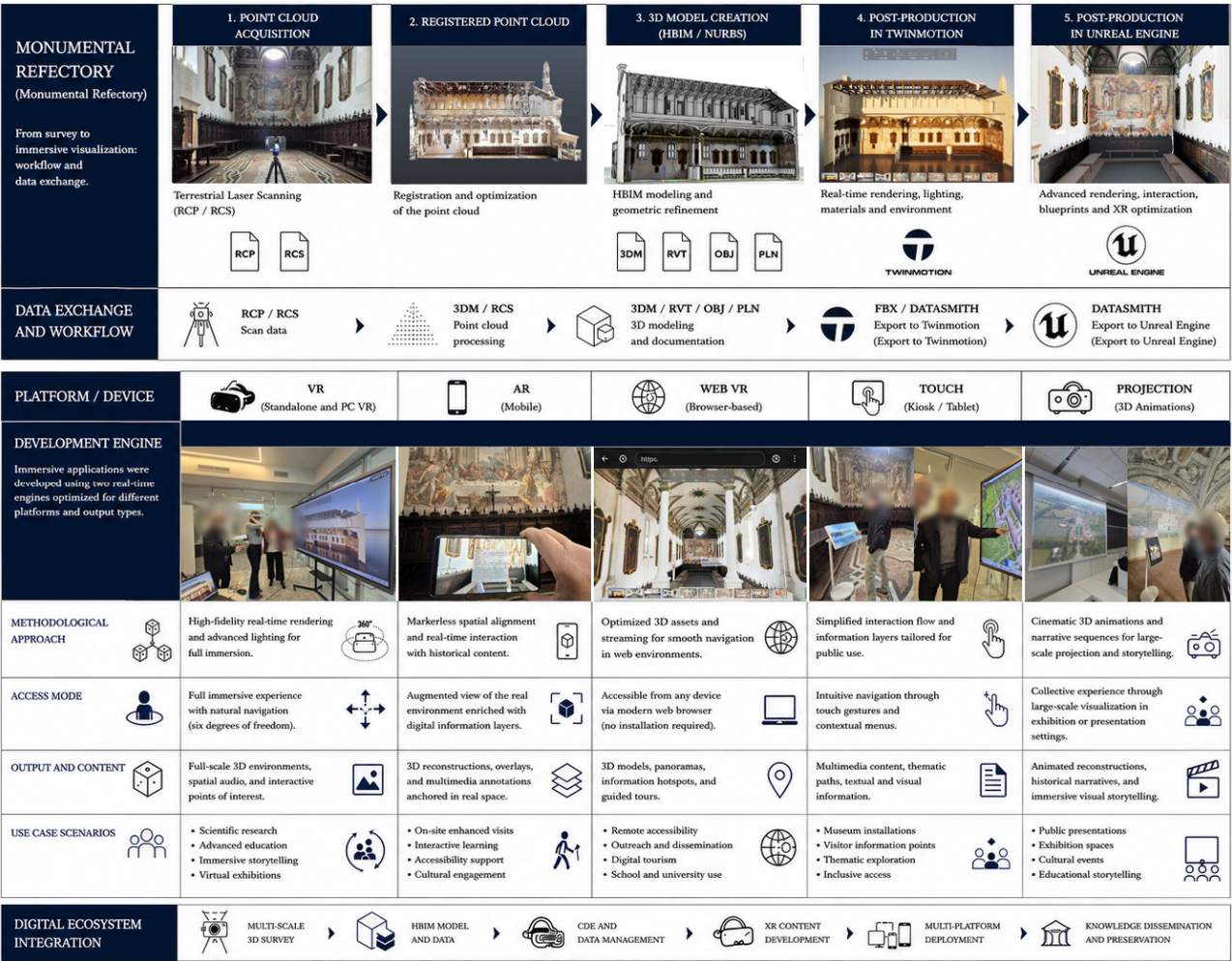


Figure 21. Integrated workflow for the development and multi-platform deployment of immersive applications for the Monumental Refectory, from point cloud acquisition and HBIM modelling to VR, AR, WebXR, touch systems, and large-scale projections using Twinmotion and Unreal Engine.

Depending on the characteristics of each dataset, optimisation was carried out using Rhinoceros, Blender, MeshLab, or Agisoft Metashape.

Texture management also followed a differentiated strategy. Original high-resolution textures were preserved for architecturally and artistically significant elements to maximise visual fidelity, whereas textures associated with secondary scene components were reduced in both resolution and DPI to optimise rendering performance while maintaining the overall perceptual quality of the immersive environment.

No additional LOD simplification strategy was implemented after export. Instead, the models were imported into the XR environment using the same geometric representations developed during the HBIM modelling phase.

Rather than generating multiple LOD versions, optimisation focused on the correct orientation of surface normals, collision generation, and selective mesh optimisation of highly detailed decorative elements, thereby improving navigation quality and real-time interaction while preserving the validated geometric fidelity of the original models.

The immersive environment was developed and tested on high-performance workstations. For projects of comparable scale and complexity, the recommended hardware configuration includes a dedicated GPU compatible with DirectX 12 (e.g., NVIDIA RTX series with at least 12 GB of VRAM), 32–64 GB of system RAM, a multi-core Intel Core i7/i9 or AMD Ryzen 7/9 processor, and NVMe SSD storage. These specifications ensure

efficient management of large-scale HBIM datasets and smooth real-time visualisation within Twinmotion and Unreal Engine.

Although the immersive applications were successfully implemented and tested, no formal benchmark of rendering performance (e.g., frame rate, loading time, or GPU utilisation) was conducted, and these aspects are identified as future work.

The resulting immersive applications were developed to support the interpretation of the principal architectural spaces of the Certosa—including the church, cloisters, monumental refectory, and representative monastic environments—while simultaneously providing virtual access to spaces that are normally inaccessible during conventional visits, such as attic systems, roof structures, hidden circulation routes, underground areas, and service spaces (Figure 21).

Beyond enhancing accessibility, these environments offer alternative modes of spatial interpretation that support the interpretation of the monument, historical evolution, and conservation complexity.

A defining characteristic of the proposed methodology is its adaptive nature. Immersive environments are conceived as continuously evolving information systems rather than static digital products. Interfaces, interaction logic, narrative contents, and visualisation strategies can be progressively updated according to curatorial requirements, educational objectives, conservation activities, or future museum programmes without interrupting the continuity of the underlying information structure.

Within this perspective, the immersive navigation environment presented in this research corresponds to the implemented component of the proposed ecosystem, whereas the virtual museum and WebXR applications are currently under development and therefore represent future extensions of the framework rather than fully implemented functionalities.

Although the proposed interoperability workflow preserves the validated geometric representation together with the selected semantic information required for interpretation and information retrieval, the complete authoring capabilities of the original HBIM environment are not transferred to the XR applications.

Platform-specific modelling parameters, editing relationships, and native BIM functionalities remain available only within the authoring environment, whereas the immersive applications provide structured access to validated information specifically prepared for communication, interpretation, and dissemination.

Overall, the proposed workflow demonstrates that information sharing extends beyond immersive visualisation towards a scalable process in which validated HBIM Knowledge Objects support conservation, management, education, accessibility, and public dissemination through a common semantic and geometric information infrastructure.

The implemented workflow preserves the direct relationship between validated HBIM Knowledge Objects and their corresponding immersive environments, ensuring that future updates of the HBIM model can be consistently propagated throughout the entire XR ecosystem.

The present study focuses on the technical implementation and validation of the XR environment within the proposed digital ecosystem. Although the immersive applications support interactive navigation and structured access to validated heritage information, no formal user-centred evaluation involving visitors, conservators, heritage professionals, researchers, or students was conducted. Consequently, aspects such as usability, accessibility, user satisfaction, knowledge acquisition, educational effectiveness, and interpretative value remain outside the scope of the present research and should be addressed through future user studies.

5. Discussion

The results support a broader reflection on three interconnected aspects: the methodological effectiveness of the proposed framework, the role of interoperability as a structural rather than purely technical component of the workflow, and the implications of ecosystem-based digitisation for the long-term management of complex CH assets.

5.1. Validation of the Ecosystem-Based Framework

The proposed study demonstrates that the effective digitisation of complex CH assets depends less on the capabilities of individual software platforms than on their coordinated integration within an interoperable workflow. The comparative assessment of BIM and geometry-based modelling environments (Figure 14) confirms that their respective strengths are complementary rather than mutually exclusive. No single platform proved capable of independently managing the geometric complexity, semantic organisation, and immersive dissemination required by the Certosa di Pavia. Instead, the results support the adoption of hybrid workflows in which specialised environments contribute according to their methodological strengths.

Within this context, the GOG 9–10 modelling strategy effectively bridges the traditional gap between geometric fidelity and semantic information management. By integrating NURBS-based reconstruction with structured HBIM implementation, the proposed workflow generates HBIM Knowledge Objects characterised by both high geometric reliability and rich semantic content. The millimetre-scale deviations obtained through GOA validation ($\sigma = 0.005$ m; Figure 16) demonstrate that the adopted modelling strategy satisfies the accuracy requirements associated with conservation, structural assessment, quantity estimation, and stratigraphic interpretation. More importantly, these results reinforce the concept of HBIM modelling as a knowledge-generation process in which geometric reconstruction and semantic interpretation evolve simultaneously.

A further contribution emerges from the iterative organisation of the proposed framework. Rather than treating validation as a final verification stage, the methodology integrates continuous validation throughout the entire digital process. This iterative approach progressively refines geometry, semantic information, and interoperability while reducing information fragmentation during successive data exchanges. Its effectiveness becomes particularly evident in large and historically stratified heritage systems such as the Certosa di Pavia, where heterogeneous datasets, multiple representation scales, and multidisciplinary conservation requirements must be managed simultaneously. Overall, the results indicate that the principal contribution of the proposed framework lies not in introducing new survey or modelling technologies, but in demonstrating how existing methodologies can operate as components of a coherent digital ecosystem. Within this perspective, interoperability becomes a methodological principle that preserves validated information across the complete heritage lifecycle rather than a simple mechanism for exchanging files between software platforms.

5.2. Interoperability as the Enabling Condition of the Digital Ecosystem

A central outcome of this research is the reinterpretation of interoperability as the enabling condition of the proposed digital ecosystem rather than as a simple mechanism for file exchange (Figure 22). The findings indicate that information continuity within the Scan-to-HBIM process depends less on software compatibility than on the coordinated interaction of specialized digital environments throughout the heritage lifecycle. Within this perspective, interoperability becomes a methodological principle operating simultaneously at geometric, semantic, and functional levels.

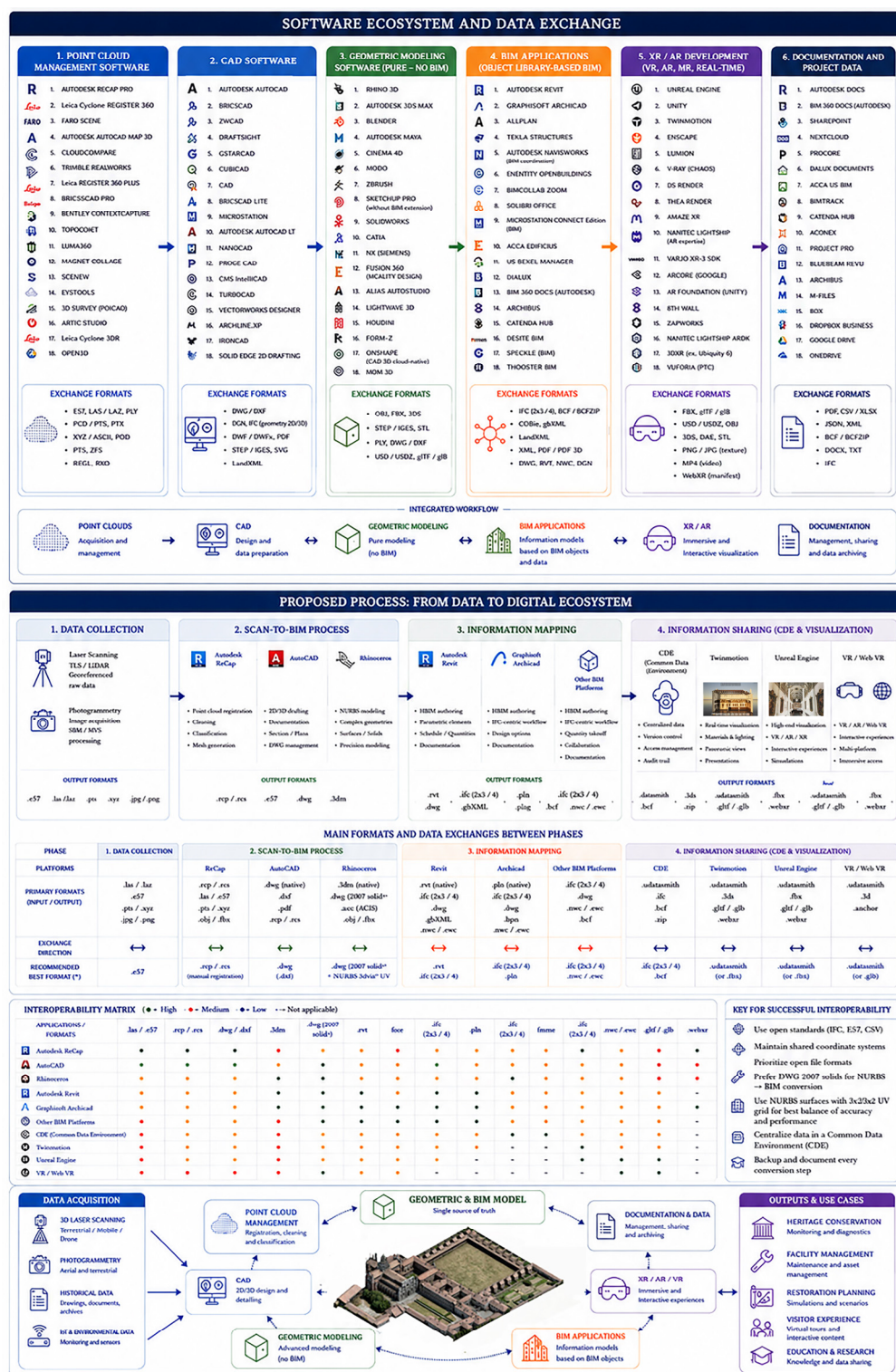


Figure 22. Interoperability workflow for the proposed ecosystem-based scan-to-HBIM methodology.

At the geometric level, the analysis confirms that preserving metric reliability depends primarily on carefully designed exchange pathways rather than on repeated data conversions. The adoption of dedicated formats for point-cloud management, NURBS reconstruction, and HBIM implementation enabled validated survey information to remain geometrically consistent throughout successive modelling stages. These findings indicate that geometric interoperability should be evaluated according to its capacity to

preserve validated survey data rather than simply its ability to transfer geometry between software platforms.

Semantic interoperability represents an even more significant challenge. While IFC remains the principal mechanism for exchanging HBIM information, the results confirm that current schemas still present limitations when representing highly irregular heritage geometries, complex stratigraphic relationships, and conservation-oriented semantic structures.

Consequently, complementary semantic repositories remain necessary to preserve historical documentation, diagnostic information, metadata, LOIN, and advanced querying capabilities. This finding reinforces the interpretation of semantic interoperability as the preservation of knowledge relationships rather than the transfer of geometric entities alone. At the functional level, the proposed workflow demonstrates that validated HBIM Knowledge Objects can be consistently extended towards immersive XR environments while maintaining the relationships between geometry and semantic information. Although further optimisation is still required for cloud-based and WebXR deployment, the results confirm that immersive applications can become integral components of the same information infrastructure rather than independent visualisation products.

An important operational outcome concerns the impact of unnecessary data conversion on contemporary CH digitisation workflows. The study demonstrates that excessive format transformations remain one of the principal causes of information loss, geometric degradation, and workflow inefficiency. Accordingly, semantic continuity should be understood as the controlled preservation of the validated information intentionally transferred between successive environments rather than as the complete preservation of every native software attribute. No formal information-loss audit comparing the original authoring models with the exported datasets was conducted, and therefore the degree of information preservation has not been quantitatively assessed.

By minimising redundant exchanges and defining phase-specific interoperability pathways, the proposed framework preserves validated datasets throughout successive workflow stages while reducing information fragmentation.

Within this architecture, the CDE assumes a strategic coordinating role. Beyond functioning as a shared repository, the CDE provides version control, traceability, collaborative access, and information consistency, becoming the organisational backbone through which multidisciplinary information remains synchronised throughout the heritage lifecycle.

Overall, these findings indicate that interoperability should not be assessed according to the number of supported exchange formats or software compatibility alone. Instead, its effectiveness should be evaluated through its capacity to preserve validated geometric, semantic, and functional information throughout the complete CH lifecycle. From this perspective, knowledge continuity emerges as the principal criterion for designing, implementing, and evaluating interoperable Scan-to-HBIM workflows.

5.3. Limitations, Scalability, and Future Research

Although the proposed ecosystem-based methodology proved effective in supporting the complete Scan-to-HBIM workflow, several technical and methodological challenges remain. From a computational perspective, managing high-density point clouds, NURBS-based geometries, and semantically enriched HBIM models continues to require substantial processing resources, particularly during the transfer of large datasets to real-time XR environments. These challenges become increasingly significant when documenting large and historically stratified CH sites, where balancing geometric fidelity, semantic richness, and real-time performance remains a critical issue.

A second limitation concerns semantic interoperability. Although IFC currently represents the most mature openBIM standard for data exchange, existing schemas remain

only partially capable of representing irregular heritage geometries, complex construction stratifications, and conservation-oriented semantic relationships. Therefore, complementary semantic repositories and metadata structures are still required to preserve historical documentation, diagnostic information, conservation records, and LOIN, preventing the complete standardisation of CH information within a single interoperable schema.

From a methodological perspective, the proposed GOG 9–10 strategy proved effective in supporting the representation of highly irregular architectural geometries while preserving the geometric accuracy demonstrated through the cloud-to-model validation. However, the project did not include controlled comparisons with conventional BIM object modelling in terms of modelling time, labour costs, computational resources, or file size. Consequently, the operational advantages observed during the implementation of the workflow should be regarded as qualitative observations rather than experimentally validated results. Future studies should quantitatively evaluate these aspects using comparable modelling tasks and predefined performance indicators.

Nevertheless, the workflow still relies on expert interpretation during both geometric reconstruction and semantic enrichment. Despite recent advances in automation, the results confirm that CH digitisation remains fundamentally a knowledge-driven process in which critical interpretation continues to play an essential role. Accordingly, the scalability of the method may be constrained in institutional contexts characterised by limited technical expertise or restricted computational resources.

An additional limitation concerns the evaluation of the immersive environments developed within the proposed framework. Although the XR applications were technically validated through their integration with the HBIM ecosystem and their ability to preserve validated geometric and semantic information, the present research did not include formal user-centred evaluation involving conservators, heritage managers, museum professionals, researchers, students, or visitors. Thus, the usability, accessibility, interpretative effectiveness, and educational value of the immersive environments were not quantitatively assessed. Future work should therefore complement the technical validation presented in this study with structured user evaluations based on established usability and user-experience methodologies, providing a comprehensive assessment of the effectiveness of XR applications for different CH stakeholders.

Beyond the challenges discussed above, several additional research directions emerge from the proposed framework. Priority developments include improving semantic interoperability within IFC schemas, integrating AI into point-cloud classification and semantic enrichment workflows, optimising adaptive LOIN, and enhancing real-time interoperability for WebXR and cloud-based environments. Equally important is the progressive integration of dynamic information sources—including Structural Health Monitoring (SHM), environmental monitoring, IoT sensors, and preventive conservation records—allowing the proposed framework to evolve from static documentation towards continuously updated DT environments.

Similarly, although the CDE supported collaborative information management throughout the project, the present study did not include a formal assessment of versioning, traceability, or interoperability based on predefined performance criteria. These aspects remain important directions for future research. Likewise, while the proposed XR environment was successfully implemented and integrated within the ecosystem-based workflow, no formal user-centred evaluation involving visitors, conservators, heritage professionals, researchers, students, or other stakeholder groups was conducted. Consequently, usability, accessibility, user satisfaction, knowledge acquisition, interpretative value, and user engagement were not quantitatively assessed and therefore remain beyond the scope of the present research.

Rather than limiting the applicability of the proposed approach, these challenges define the next stage in the evolution of ecosystem-based Scan-to-HBIM workflows. Although the methodology was validated through the Certosa di Pavia case study, it was intentionally conceived as a platform-independent, scalable framework capable of supporting different CH contexts characterised by complex geometries, heterogeneous information sources, and multidisciplinary conservation requirements.

Its transferability should therefore not be interpreted as the direct replication of an identical workflow, but rather as the adaptation of common methodological principles to different institutional capacities, project scales, available financial and technological resources, and conservation priorities. Accordingly, large and highly stratified heritage sites may benefit from the complete integration of reality capture, HBIM, semantic information management, CDEs, and XR technologies, whereas smaller institutions may implement only those components that are most appropriate to their operational needs while preserving the same principles of geometric reliability, semantic consistency, and interoperability.

Future research should therefore focus on strengthening semantic interoperability within openBIM environments, advancing automation in Scan-to-HBIM processes, developing quantitative methodologies for interoperability assessment, conducting systematic user-centred evaluations based on established usability and user-experience protocols, and improving the long-term sustainability of integrated digital ecosystems.

6. Conclusions

This research proposes and validates a platform-independent, ecosystem-based methodology for the digitisation of complex CH, integrating reality capture, hybrid Scan-to-HBIM modelling, semantic information management, interoperability, and XR within a continuous digital workflow. Validated through the Certosa di Pavia case study, the proposed framework demonstrates how existing technologies can be systematically integrated while preserving validated geometric and semantic information throughout the workflow.

The principal contribution of this study does not lie in introducing new survey technologies, modelling procedures, or visualisation platforms. Rather, it demonstrates how existing methods can be systematically integrated into a unified digital ecosystem in which validated geometry, semantic knowledge, and interoperable information operate as complementary components of a continuous knowledge process.

Accordingly, interoperability is interpreted not simply as a mechanism for exchanging files between software platforms, but as a methodological principle supporting the continuity of validated geometric and semantic information throughout the digital workflow. The principal validated technical achievement of the proposed framework is the preservation of geometric reliability across the transition from reality capture to HBIM environments and XR applications through continuous geometric validation and structured semantic organisation.

The results further demonstrate that HBIM should be understood as a dynamic knowledge environment rather than a three-dimensional representation alone. By integrating historical documentation, conservation records, diagnostic investigations, metadata, and LOIN within validated HBIM Knowledge Objects, the proposed framework supports multidisciplinary collaboration while maintaining semantic coherence throughout successive phases of documentation, analysis, conservation, management, and dissemination. Continuous validation proved fundamental in preserving the consistency of both geometric and semantic information, reducing fragmentation across heterogeneous digital environments.

The Certosa di Pavia provided a particularly demanding validation environment because of its architectural complexity, historical stratification, and heterogeneous information sources. The case study demonstrated the applicability of the proposed workflow for

documenting both accessible and inaccessible architectural spaces while integrating validated geometric and semantic information within a unified digital environment supporting conservation, documentation, management, research, and dissemination activities.

This study enabled, for the first time, the comprehensive digital documentation of inaccessible architectural spaces while establishing a georeferenced and semantically structured information system capable of supporting conservation, research, education, management, and immersive dissemination. Although validated through this case study, the framework has been intentionally conceived as platform-independent and transferable to other CH contexts characterised by complex geometries, multidisciplinary conservation requirements, and heterogeneous information sources.

Its implementation, however, should be adapted according to project scale, institutional capacity, available technological resources, and conservation priorities.

Despite these results, several limitations should be acknowledged. The framework was validated through a single large-scale case study and did not include formal comparative assessments of modelling efficiency, information-loss audits across interoperability stages, or user-centred evaluations of the proposed XR environments. Consequently, the operational benefits of the workflow with respect to modelling effort, semantic continuity, and user experience should be regarded as promising observations rather than experimentally validated outcomes. These aspects represent important directions for future research.

Future research should therefore focus on quantitatively evaluating GOG-based modelling strategies, strengthening semantic interoperability within openBIM standards, assessing information preservation across data conversion stages, conducting user-centred evaluations of XR environments, and progressively incorporating dynamic information sources—including Structural Health Monitoring (SHM), environmental monitoring, IoT sensors, and preventive conservation records—towards continuously updated DT ecosystems. Overall, this study suggests that the future of CH digitisation depends less on the development of new individual technologies than on the ability to integrate existing ones within interoperable, knowledge-oriented digital ecosystems. From this perspective, the proposed framework provides a methodological basis for supporting documentation, conservation, management, and dissemination through the continuous preservation and reuse of validated geometric and semantic information.

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Abbreviations

The following abbreviations are used in this manuscript:

AR	Augmented Reality
BIM	Building Information Modeling
CAD	Computer-Aided Design
CDE	Common Data Environment
CH	Cultural Heritage
DCH	Digital Cultural Heritage
DH	Digital Heritage
FM	Facility Management
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GOA	Grade of Accuracy
GOG	Grades of Generation
GSD	Ground Sampling Distance
HBIM	Heritage Building Information Modeling
ICT	Information and Communication Technology
IFC	Industry Foundation Classes
IVO	Interactive Virtual Object
LCA	Life Cycle Assessment
LOA	Level of Accuracy
LOD	Level of Detail
LOG	Level of Geometry
LOI	Level of Information
LOIN	Level of Information Need
LOR	Level of Reliability
ML	Machine Learning
MR	Mixed Reality
NURBS	Non-Uniform Rational B-Splines
RMSE	Root Mean Square Error
RTK	Real-Time Kinematic
UAV	Unmanned Aerial Vehicle
UTM	Universal Transverse Mercator
VPL	Visual Programming Language
VR	Virtual Reality
WebXR	Web Extended Reality
XR	Extended Reality

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