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Digital narratives of the past: leveraging HBIM for inclusive and data-driven heritage documentation

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Abstract

Purpose – This study investigates the application of Heritage Building Information Modelling (HBIM) in the digital documentation and lifecycle management of historic structures. It aims to evaluate how HBIM supports efficient and sustainable heritage conservation through accurate 3D modelling and data integration. The research further examines and compares the capabilities and limitations of widely used HBIM software, with particular attention to documentation performance. A case study of scan-to-BIM modelling of Castiglioni College in Pavia, Italy, is undertaken to explore practical implementation and assess the effectiveness of HBIM in capturing and managing complex heritage information.

Design/methodology/approach – A mixed-method approach was adopted, combining a systematic literature review with practical implementation. Qualitative analysis of existing HBIM studies was integrated with quantitative parametric modelling processes. A structured HBIM framework was developed to represent geometric, material, and semantic attributes of heritage assets. Comparative evaluation of leading HBIM software tools was conducted based on functionality and limitations. The methodology was validated through a scan-to-BIM case study of Castiglioni College, where point cloud data were processed and converted into an HBIM model to assess accuracy, workflow efficiency, and integration of multi-source data.

Findings – The results demonstrate that HBIM enables comprehensive documentation by integrating geometric, semantic, and historical data into a unified digital environment, improving visualization and supporting conservation decision-making. The scan-to-BIM case study confirmed the effectiveness of HBIM in accurately modelling complex heritage structures, though challenges remain in handling irregular geometries and data integration. Software comparison revealed that no single HBIM platform is universally optimal; instead, performance varies depending on project requirements such as restoration focus, modelling complexity, and available resources. Effective implementation, therefore, requires context-specific tool selection and careful workflow design.

Originality/value – This study contributes to the growing field of digital heritage by providing an integrated evaluation of HBIM processes, software tools, and practical application through a real-world case study. It bridges the gap between theoretical frameworks and applied methodologies by demonstrating a structured workflow for scan-to-BIM modelling. The research offers critical insights into software selection and data integration challenges, supporting more informed decision-making in heritage conservation. By aligning HBIM implementation with sustainability and lifecycle management principles, the study advances the role of digital technologies in preserving architectural heritage.

Keywords Building information modelling, BIM, HBIM, Historic building information modelling, Heritage building information modelling, Cultural heritage, Heritage informatics, Documentation, Castiglioni college

Paper type Conceptual paper

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Introduction

As a distinctive manifestation of human achievement, cultural heritage encompasses physical artefacts and associated knowledge, traditions, and values. Conservation and valorisation of heritage structures ensure their accessibility and long-term sustainability. Preserving heritage buildings is crucial to enable current and future generations to appreciate and learn from their historical and architectural legacy (Hunt *et al.*, 2023). Historic and architectural structures often embody intrinsic values and are characterised by diverse materials, design approaches, decorative elements, and textures, which are not always uniform. Identifying and documenting these unique characteristics that define the cultural, architectural, and historical significance of heritage structures is essential to ensure their preservation for future generations. This process supports informed conservation strategies and promotes a deeper understanding of the site's value and context. Despite adherence to traditional surveying, restitution, and restoration processes, heritage conservation faces challenges related to incomplete documentation and missing as-built information, resulting in inefficiencies, cost overruns, and project delays (Khan *et al.*, 2022). Documentation remains a fundamental tool at every stage of the conservation process, demonstrating the knowledge linked to the physical and functional attributes of heritage assets, facilitating informed decision-making, and enabling comprehensive digital representation. Adopting advanced technologies considerably enhances the integrated conservation process, management, and comprehensive documentation of heritage assets, and facilitates architectural analysis and research studies for historians and conservators. Building Information Modelling (BIM) is a pivotal tool driving digital transformation, providing a holistic approach to creating and managing detailed information about architectural heritage structures. Nowadays, it has evolved significantly in the management and documentation of cultural heritage and can represent, in a virtual environment, the actual conservation state of the analyzed buildings (López *et al.*, 2018). Cultural heritage greatly benefits from BIM, especially given its operational application in existing and new constructions; notably, it is recognised as a key performance parameter within the context of built heritage. BIM was initially developed for use in new construction projects; however, its application has widened to encompass restoration efforts, including the preservation of private and historical structures (Hamma-adama and Kouider, 2019). Its capacity to integrate diverse data sources enhances conservation efforts and supports informed decision-making throughout the building's lifecycle. In recent years, the BIM approach has been rapidly spreading (Chen and Tang, 2019) and holds significant potential for creating extensive, complex, and detailed documentation of individual buildings (Sztwiertnia *et al.*, 2021). Numerous digital and visualisation techniques are employed in architectural heritage to accurately represent the characteristics and current conditions of structures by integrating historical data, geometric methods, drawings, and design applications. However, BIM offers a digital representation of a building's geometry and associated features, capable of integrating and managing otherwise discrete building elements and disciplines within a single federated model (Succar, 2009). Data acquired through 3D modelling, 360-degree panoramic views, point clouds, laser scanning, virtual reality, augmented reality, virtual tours, and digital twins support comprehensive digital documentation, aiding preservation, management, and valorisation while ensuring the optimal safety of historic structures. Conceptually, BIM is an integrative tool for the design, representation, production, and long-term management of the built environment (Fai *et al.*, 2011). Its ability to consolidate diverse data streams renders it particularly valuable for the effective conservation and sustainable management of heritage structures.

The term Historic (or Heritage) Building Information Modelling (HBIM) was introduced by Dore and Murphy (2012). HBIM refers to applying BIM methodology focused on the three-dimensional and information-rich modelling of existing historical heritage, playing a pivotal role in conserving cultural heritage buildings. It facilitates accurate documentation, condition assessment, and informed decision-making throughout preservation. HBIM utilises digital models to represent heritage assets, enabling improved documentation, detailed analysis, and

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visualisation of structures and materials based on reliable data. These digital models, combined with advanced visualisation techniques, also facilitate virtual access and user engagement, while providing technical and organisational support for future reconstruction efforts. While BIM primarily concentrates on new building design and construction, HBIM is centred on existing structures needing interventions like conservation, restoration, repurposing, and rehabilitation (Penjor *et al.*, 2024). HBIM, as a multidisciplinary approach to heritage documentation, facilitates the virtual representation of information associated with cultural heritage buildings and integrates with conservation practices to enhance their longevity. It provides a novel system for modelling historic structures within a three-dimensional digital environment. HBIM enables the creation of comprehensive documentation encompassing both graphical and non-graphical aspects of heritage structures, thereby supporting their conservation and long-term sustainability. By assimilating all information related to a cultural heritage building, HBIM enriches understanding of its complex structural and functional characteristics, forming a reliable foundation for informed decision-making. Creating a centralised digital model containing all relevant building information is critical for effectively managing and maintaining heritage assets.

The evolution of HBIM research has progressively expanded beyond geometric documentation towards intelligent and data-driven heritage management. Early studies established the theoretical foundations of HBIM and demonstrated its potential for integrating geometric, historical, and semantic information within digital heritage environments (Fai *et al.*, 2011; Dore and Murphy, 2012; Oreni *et al.*, 2012; Dore *et al.*, 2015). Subsequently, research focused on developing structured workflows, interoperability mechanisms, and information management frameworks for heritage conservation (López *et al.*, 2018; Wang *et al.*, 2019). More recent investigations have explored scan-to-BIM methodologies, point-cloud processing, semantic enrichment, and integrated heritage information systems to enhance documentation accuracy and decision-making processes (Pepe *et al.*, 2021; Sztwiertnia *et al.*, 2021; Khan *et al.*, 2022; Martinelli *et al.*, 2022; Karasaka and Ulutas, 2023; Penjor *et al.*, 2024). Building upon these developments, current research trends increasingly integrate Artificial Intelligence (AI), Machine Learning (ML), Deep Learning, Geographic Information Systems (GIS), and Digital Twin technologies to support automated feature recognition, predictive conservation, anomaly detection, semantic classification, real-time monitoring, and advanced spatial analysis of cultural heritage assets (Argasiński and Piotr, 2023; Hunt *et al.*, 2023; Cotella *et al.*, 2025; Parente *et al.*, 2025). These emerging technologies are expected to significantly enhance the capacity of HBIM environments to support evidence-based conservation planning, lifecycle management, and sustainable heritage governance.

The development of HBIM has evolved significantly over the last decade, progressing from a digital documentation methodology towards an integrated framework for heritage conservation, management, and decision support. Early HBIM studies focused primarily on the generation of information-rich digital representations of historic structures through the integration of survey data, semantic information, and three-dimensional modelling environments (Fai *et al.*, 2011; Dore and Murphy, 2012; Murphy *et al.*, 2013; Oreni *et al.*, 2012). Subsequent research expanded these concepts by introducing interoperability frameworks, conservation-oriented information management, open-source HBIM approaches, and standardised workflows for documenting complex heritage assets (Dore *et al.*, 2015; Castagnetti *et al.*, 2017; Diara and Rinaudo, 2018; López *et al.*, 2018; Pocobelli *et al.*, 2018).

More recent investigations have explored scan-to-BIM methodologies, reality-capture technologies, point-cloud processing, semantic enrichment, and automated modelling approaches to improve the efficiency and accuracy of heritage documentation (Wang *et al.*, 2019; Pepe *et al.*, 2021; Sztwiertnia *et al.*, 2021; Khan *et al.*, 2022; Martinelli *et al.*, 2022). The integration of advanced surveying technologies, digital information systems, and heritage

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management frameworks has further strengthened the role of HBIM as a decision-support tool for conservation planning and lifecycle management (Della Torre, 2021; Hunt *et al.*, 2023; Argasiński and Piotr, 2023; Karasaka and Ulutas, 2023; Cotella *et al.*, 2025). Nevertheless, researchers continue to identify several persistent challenges, including the modelling of irregular geometries, semantic enrichment of heritage information, interoperability limitations, high implementation costs, data standardisation issues, and the substantial manual effort required for object creation and information management (Khan *et al.*, 2022; Karasaka and Ulutas, 2023; Penjor *et al.*, 2024; Parente *et al.*, 2025). These challenges continue to limit the broader adoption of HBIM workflows and highlight the need for practical, reproducible frameworks that effectively integrate survey data, information management, and conservation requirements.

Despite the growing adoption of HBIM in cultural heritage documentation, significant gaps remain in its practical implementation and evaluation. Existing studies predominantly focus on conceptual frameworks or isolated applications, with limited comparative analysis of HBIM software tools and their effectiveness in real-world heritage documentation workflows. Furthermore, challenges related to integrating heterogeneous data sources, managing irregular geometries, and ensuring accuracy in scan-to-BIM processes are not sufficiently addressed in current research. This highlights the need for a systematic and application-oriented investigation that bridges theoretical potential and practical execution. Hence, this study evaluates the effectiveness of HBIM as a digital tool for heritage documentation and conservation by integrating methodological analysis, software comparison, and applied case study validation. The research specifically seeks to assess how HBIM workflows can improve accuracy, efficiency, and data integration in documenting complex historic structures.

To achieve this aim, the study is guided by the following research questions:

RQ1. How can HBIM methodologies be effectively applied to document and manage architectural heritage assets?

RQ2. What are the strengths and limitations of leading HBIM software tools in supporting scan-to-BIM workflows and heritage documentation?

RQ3. How effectively can integrated HBIM approaches represent complex geometric, material, and semantic characteristics in a real-world case study?

This study adopts a combined methodological, comparative, and applied research approach. It integrates a systematic literature review, comparative software analysis, and an empirical scan-to-BIM case study of Castiglioni College in Pavia, Italy. By doing so, the research provides both theoretical insights and practical validation, contributing to a more structured and evidence-based understanding of HBIM implementation in cultural heritage conservation.

Framework for HBIM documentation

Understanding the original construction methods, the various stages of transformation, and the current condition of a building is essential for establishing effective conservation, management, and maintenance strategies. This necessitates comprehensive and detailed documentation. HBIM offers a detailed analysis of the materials, functional, structural, and semantic elements of cultural heritage, supported by precise geometric data and advanced digital visualisation techniques. By combining advanced surveying technologies with parametric modelling, HBIM enables accurate geometric representation and systematic documentation of structural conditions (Pepe *et al.*, 2021). To ensure accuracy, various surveys of a building and its constituent structural and functional elements are essential, requiring effective data acquisition methods capable of capturing and visualising every detail. The procedure for the construction of an HBIM relating to a generative structure (church, castle, building, etc.) can be composed as follows (Wang *et al.*, 2019): (1) identification of information requirements; (2) determination of required scan data quality; (3) scan data

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acquisition; and (4) as-is BIM reconstruction. Interdisciplinary collaboration among archaeologists, architects, archivists, conservators, construction professionals, engineers, historians, restorers, and information specialists is essential to deepen the understanding of historical buildings and address the challenges in creating HBIM models and documentation. This collaborative approach enriches the accuracy and comprehensiveness of HBIM and fosters innovation in heritage conservation practices. There has been a growing interest in HBIM among these specialists. Figure 1 illustrates the conceptual framework for the HBIM documentation process, designed to enhance accessibility to complex heritage systems. The development of a comprehensive HBIM model draws upon a wide array of information sources, including historical documents, photographs, drawings, music, oral histories, architectural plans, sections, elevations, reports, bibliographic resources, and analyses, sourced from individuals, experts, and GLAM institutions (Galleries, Libraries, Archives, and Museums). Adopting a digital approach addresses the inherent complexity of information associated with heritage architectural materials and facilitates a comprehensive analysis, integrating the data into a clearly structured digital framework (Della Torre, 2021).

Methodological framework for HBIM implementation

To ensure reproducibility and analytical rigour, the HBIM workflow adopted in this study is structured into clearly defined phases, integrating data acquisition, processing, modelling, and the evaluation process. The case study focuses on Castiglioni College in Pavia, Italy, selected due to its historical significance and geometric complexity. The present research builds upon the survey campaign previously documented by Dell'Amico (2023), utilising the resulting survey datasets for the development and evaluation of the proposed HBIM documentation framework. The scope of the study includes exterior and selected interior architectural elements necessary to evaluate scan-to-BIM integration and documentation accuracy. The research was conducted by a multidisciplinary team comprising architectural researchers with expertise in heritage conservation, digital modelling, and BIM processes. Data acquisition was performed using terrestrial laser scanning and photogrammetric techniques to capture high-resolution point cloud data representing the as-is condition of the structure.

The survey data employed in this study were derived from the survey campaign documented by Dell'Amico (2023) for Castiglioni College, Pavia. The acquisition strategy combined terrestrial laser scanning (TLS), mobile laser scanning (MLS), UAV photogrammetry, and photographic documentation to ensure comprehensive coverage of the historic building. A FARO CAM 150 terrestrial laser scanner was used to survey façades, courtyards, and attic spaces, while interior environments were captured using a Leica BLK2GO mobile laser scanner. Roof geometries and other inaccessible areas were documented through UAV photogrammetry using a DJI Phantom 4 Pro RTK platform. Additional photographic documentation and photogrammetric support were obtained using a Canon EOS 1200D camera. The survey campaign comprised 135 RGB scans and 8 black-and-white scans. Point-cloud registration was performed in Cyclone Core software using approximately 30 homologous control points, achieving registration errors ranging from 0.008 m to 0.034 m (Dell'Amico, 2023). The resulting datasets were integrated into a unified three-dimensional database, which subsequently formed the basis for the HBIM development undertaken in the present study (Dell'Amico, 2023).

The acquired point-cloud datasets underwent preprocessing procedures, including registration, alignment, and noise filtering, to ensure data quality prior to HBIM development. The integrated survey dataset provided a comprehensive digital representation of the building, supporting the subsequent interpretation, segmentation, and modelling of architectural components.

The workflow consisted of four primary phases: (1) data acquisition and preprocessing, including point cloud generation and noise reduction; (2) data interpretation and segmentation to identify architectural components; (3) parametric HBIM modelling using BIM authoring

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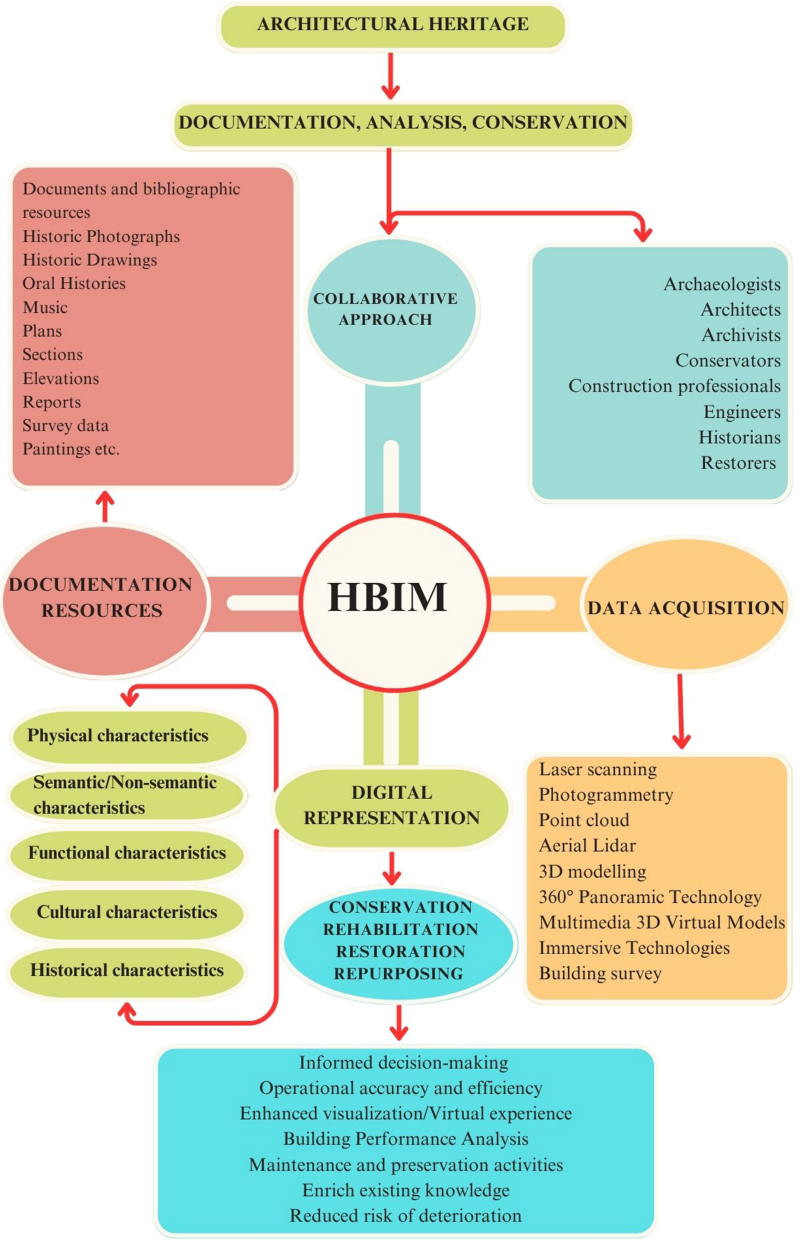


Figure 1. The documentation-oriented schematic representation of HBIM framework elements. Source: Compiled by Authors

software; and (4) validation and documentation, including comparison with reference data and assessment of modelling accuracy. Autodesk Revit and Recap were primarily employed for point cloud processing and parametric modelling, supported by auxiliary tools for visualisation and data management. The HBIM environment was designed to integrate both

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quantitative and qualitative information. Quantitative data comprised geometric measurements extracted from TLS, MLS, and photogrammetric datasets, including dimensions, spatial relationships, and architectural geometries. Qualitative information included historical records, archival documentation, material descriptions, conservation data, construction phases, and heritage significance attributes. These datasets were linked through object-based HBIM parameters and metadata fields, enabling each architectural component to function simultaneously as a geometric representation and an information repository.

Modelling followed standardised Level of Development (LOD) and Level of Information (LOI) principles to ensure consistency, accuracy, and interoperability. The duration of each phase varied depending on data complexity, with modelling and data processing representing the most time-intensive stages. The overall workflow was implemented over a structured timeframe, with data acquisition conducted over a limited number of field sessions, followed by extended processing and modelling phases. The modelling stage was the most time-intensive due to the need to interpret irregular geometries and translate them into parametric components. Decision-making processes were guided by optimisation between geometric accuracy and modelling efficiency, particularly in handling irregular heritage elements. This structured methodological framework enables systematic evaluation of HBIM processes and ensures the reproducibility of the study, addressing key challenges in heritage documentation and scan-to-BIM workflows.

Various BIM authoring tools, available in proprietary and open-source formats, are employed to develop detailed parametric models of heritage structures by integrating historical, diagnostic, and documentary information. Commonly used software for HBIM includes Revit (Autodesk), ArchiCAD, AECOsim Building Designer, Tekla, Navisworks, Recap, and SketchUp, often supplemented by other computer-aided design and visualisation applications. Each tool offers distinct features and limitations when creating HBIM models, influencing their suitability for specific heritage projects. Parente *et al.* (2025) identify Autodesk Revit as the most frequently reported HBIM platform in the reviewed literature, reflecting its widespread adoption within the architecture, engineering, and construction sectors. Nevertheless, recent studies have also highlighted the increasing relevance of open-source and specialised software solutions for particular heritage documentation and conservation tasks. Each HBIM software offers unique strengths that contribute to the documentation and preservation of cultural heritage. Revit stands out for its comprehensive parametric modelling and built-in documentation capabilities, making it ideal for detailed heritage records and construction documents. ArchiCAD provides user-friendly architectural workflows with clear 2D and 3D documentation for heritage visualisation. AECOsim supports multidisciplinary documentation needs in large, complex projects, while Tekla specialises in structural detailing critical for restoration. Navisworks enhances documentation workflows through model coordination and clash detection. Recap is an essential tool for converting reality capture data into accurate geometric models that form the basis of HBIM documentation. SketchUp, though limited in detailed documentation, is valuable for conceptual modelling and early-stage visualisation.

The software comparison was conducted using five evaluation criteria commonly adopted in HBIM literature: (1) parametric modelling capability, (2) interoperability with point-cloud and survey data, (3) documentation and annotation functionality, (4) multidisciplinary coordination support, and (5) suitability for heritage conservation workflows. The strengths and limitations reported in Table 1 were assessed through a synthesis of published studies, software technical documentation, and practical experience with Autodesk Revit and Autodesk Recap. Because the present study directly utilised Autodesk Revit and Autodesk Recap, the remaining software platforms are included for comparative purposes to contextualise the broader HBIM software landscape. To provide a broader understanding of the HBIM software ecosystem, a comparative review of commonly reported HBIM platforms was undertaken. Table 1 presents a comparative overview of widely used HBIM software, outlining their strengths, limitations, and roles in documentation.

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Table 1. Comparative overview of HBIM software capabilities and applications based on published literature, software technical documentation, and authors' practical experience with Autodesk Revit and Autodesk Recap

Software	Strengths	Limitations	HBIM use in documentation
Revit (Autodesk)	Industry standard Strong parametric capabilities Extensive plugin ecosystem	Steep learning curve Costly license	Comprehensive HBIM modelling with built-in annotation and data management Ideal for precise construction documents and heritage records
ArchiCAD	User-friendly interface Strong architectural workflows Good 2D/3D integration	Limited structural engineering tools	Supports architectural HBIM modelling, visualisation, and heritage documentation through precise 2D drawings and annotations
AECOsim building designer	Robust multidisciplinary tools Strong in infrastructure MEP modelling	Complex interface Less common in heritage projects	Supports multidisciplinary coordination and integrated documentation workflows for large heritage projects
Tekla structures	Excellent for structural detailing Supports complex geometries	Limited architectural modelling features	Supports structural documentation, detailing, and restoration analysis of heritage structures
Navisworks	Powerful clash detection Model aggregation 4D simulation	Not a modelling tool itself Relies on imported models	Supports project review, model coordination, and clash detection within documentation workflows
Recap (Autodesk)	Converts point cloud data into usable 3D models; integrates well with Revit	Steep learning curve, Costly license	Supports reality-capture processing and generation of accurate geometric data for HBIM documentation
SketchUp	Easy to learn Quick modelling Large plugin library	Limited BIM capabilities Less parametric	Supports conceptual modelling and early-stage heritage visualisation

The comparative assessment presented in Table 1 was developed through a synthesis of peer-reviewed HBIM literature, documented case studies, and software technical documentation. Foundational HBIM concepts and workflows were informed by studies such as Fai *et al.* (2011), Dore and Murphy (2012), Dore *et al.* (2015), Oreni *et al.* (2012), and López *et al.* (2018), which established the theoretical and methodological basis for heritage building information modelling. More recent contributions by Khan *et al.* (2022), Karasaka and Ulutas (2023), Penjor *et al.* (2024), Cotella *et al.* (2025), and Parente *et al.* (2025) provided insights into contemporary HBIM practices, software environments, interoperability requirements, information management, and implementation challenges. Additional evidence was derived from application-oriented studies, including Wang *et al.* (2019), Pepe *et al.* (2021), Martinelli *et al.* (2022), Dell'Amico (2023), Sztwiertnia *et al.* (2021), and Diara and Rinaudo (2018), which examined scan-to-BIM workflows, point-cloud processing, parametric modelling strategies, and digital heritage documentation. Technical characteristics, workflow capabilities, and interoperability features were further verified through official documentation published by Autodesk, Graphisoft, Bentley Systems, and Trimble. While Autodesk Revit and Autodesk Recap were directly employed and evaluated in the present study, the strengths, limitations, and HBIM applications of the remaining software platforms were synthesised from findings reported in the literature and technical sources. Therefore, Table 1 should be interpreted as a comparative review of commonly reported HBIM software environments rather than a direct experimental evaluation of all software packages by the authors.

Although several HBIM platforms are currently available, Autodesk Recap and Autodesk Revit were selected for implementation in the present study. Autodesk Recap was used to process reality-capture data collected during the survey stage and generate accurate point

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cloud datasets representing the existing conditions of the heritage structure. These datasets were subsequently imported into Autodesk Revit, which served as the primary HBIM authoring platform. Revit was selected because of its advanced parametric modelling environment, extensive support for metadata integration, interoperability with point-cloud data, and ability to generate comprehensive documentation outputs. These capabilities facilitate the creation of information-rich HBIM models that support documentation, conservation planning, asset management, and future restoration activities. The selection of Revit and Recap was therefore guided by both their technical suitability for heritage documentation and their widespread adoption within contemporary HBIM practice.

Together, these tools provide a comprehensive technological framework for HBIM-based heritage documentation. In the present study, Autodesk Recap and Autodesk Revit formed the core technological environment used to develop the HBIM model and associated information system. Building upon existing HBIM workflows reported in the literature, the proposed approach further integrates an online interactive information platform with advanced search and retrieval capabilities. This additional layer enhances accessibility to heritage information, supports conservation decision-making, and contributes to more effective management and dissemination of cultural heritage knowledge.

Several studies have demonstrated the effectiveness of HBIM for heritage documentation, conservation planning, and information management (Dore and Murphy, 2012; López *et al.*, 2018; Khan *et al.*, 2022; Penjor *et al.*, 2024). While these studies primarily focus on digital modelling workflows, documentation methodologies, and information management, the present research combines a comparative evaluation of HBIM software platforms with the practical implementation of a scan-to-BIM workflow for Castiglioni College in Pavia, Italy. Furthermore, the study extends conventional HBIM approaches by integrating an interactive information environment designed to enhance information retrieval, accessibility, and dissemination of heritage knowledge. This combination of software evaluation, real-world scan-to-BIM implementation, and user-oriented information management extends existing HBIM workflows and constitutes the principal contribution of the study.

Unlocking heritage: the power of HBIM

HBIM is a vital tool that facilitates comprehensive documentation, enabling the visual representation of cultural heritage buildings enriched with accurate interpretations and annotations. As a data-driven and intelligent modelling approach, it enhances the lifecycle efficiency of architectural structures by effectively disseminating information related to the history of cultural heritage assets. This information model aids in identifying the structural behaviour of buildings and assessing material deterioration, while also providing insights into their historical evolution—including progressive modifications, repairs, various construction phases, and the application of multiple construction technologies. Moreover, HBIM supports informed decision-making in conservation planning, maintenance strategies, and restoration interventions, contributing significantly to the sustainable preservation of heritage structures. Including HBIM library documentation of heritage building assets with social factors allows for creating more comprehensive records, facilitating enhanced knowledge acquisition and a stronger societal valuation of these cultural assets (Cotella *et al.*, 2025). HBIM represents a holistic approach to sustainability and is a valuable guide for restoration efforts. It assists conservators, policymakers, and other stakeholders involved in preservation and conservation by facilitating engagement, raising awareness, and supporting informed decision-making to enhance operational efficiencies.

Furthermore, HBIM fosters collaboration across disciplines, ensuring restoration strategies are practical and respectful of the heritage's cultural significance. However, there is a need for a holistic approach and analysis of HBIM concepts, technologies, and applications for heritage conservation projects (Penjor *et al.*, 2024). HBIM plays a critical role in the restoration process by providing a comprehensive understanding of a building's condition at the time of

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documentation, allowing for the evaluation of appropriate measures to safeguard it from deterioration and damage while preserving its historical and cultural significance. Its ability to efficiently plan, execute, and manage restoration projects contributes to reduced costs and time, thereby enhancing project efficiency. Moreover, HBIM supports long-term sustainability through informed maintenance strategies and predictive interventions. Overall, it serves as a fundamental tool in the information management process, enabling the creation of detailed digital representations of historic assets essential for damage prevention and targeted conservation efforts.

Navigating HBIM: technical bottlenecks and data complexity

HBIM is an information modelling technique that addresses the heritage landscape for adequate documentation and preservation, involving a complex and multifaceted process. The application of BIM to historical or heritage structures is an interesting challenge in 3D modelling and the management/valorisation of buildings of particular historical and cultural interest (Castagnetti *et al.*, 2017; Diara and Rinaudo, 2018). The significant challenges include the need for specialised knowledge, limited awareness, technical constraints, and a lack of standardisation in HBIM applications. The inherent complexity and uniqueness of historical structures further complicate the process, alongside the high costs associated with developing detailed models and insufficient training opportunities. Additionally, the heterogeneous nature of information within the historic built environment poses significant difficulties. Despite technological advancements, there remains a pressing need for low-cost and rapid analysis methods for accurately capturing building geometry. Also, the reconstruction from raw data such as point clouds and images is challenging, especially in terms of parametrical and semantic modelling (Karasaka and Ulutas, 2023). Furthermore, the process demands specialised expertise in preservation, documentation, and restoration techniques and the collection of precise and detailed information, which is often both time-consuming and costly. While BIM technology provides high accuracy, improved efficiency, advanced visualization, and streamlined management of dimensions for real-time monitoring, its adoption in heritage conservation can involve considerable costs, including investment in specialized software, skilled personnel training, and advanced equipment acquisition. HBIM still requires a methodological discussion and practice experimentation to handle detailed models of irregular historical objects useful for their preservation and maintenance activities (Oreni *et al.*, 2012).

Case study of scan-to-BIM modelling of Castiglioni college in Pavia, Italy

The techniques employed for HBIM documentation must enable geometric surveys of cultural objects with a high degree of detail and completeness to facilitate superior visualisation. The availability of accurate geometric models is critical for subsequent restoration and reconstruction processes. Therefore, comprehensive data—including construction methods, designs, plans, digital files, models, maintenance requirements, the building's evolution over time, material properties, and related information—is essential. Scan-to-BIM is a well-established workflow that moves through distinct stages: creating a Common Data Environment (CDE), performing measurement surveys, processing point clouds, creating a geometric model, enriching the data with semantic information, and applying conservation measures (Martinelli *et al.*, 2022). As the application of HBIM, which facilitates the design of 3D modelling and the lifecycle management of historic structures, exhibits considerable potential in the documentation and administration of cultural heritage, particularly within the context of built heritage. The scan-to-BIM approach with semantic annotations and IFC (Industry Foundation Classes) standards improves the use of 3D models from point clouds in heritage building preservation and management (Penjor *et al.*, 2024). HBIM comprehensively

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captures the entire spectrum of a building's physical and functional attributes and enables their digital representation with geometric precision and detailed visualisations.

Castiglioni Brugnatelli College, Pavia, was used as a case study to effectively represent the complex interior and exterior environments using a scan-to-BIM system and better transmit the embedded knowledge in the building (Plate 1). The college, founded in 1429 by Cardinal Branda Castiglioni, Collegio Castiglioni enjoyed a period of fame and economic prosperity. Its decline began in the mid-16th century. In 1803, it was merged with the Ghislieri College. In 1805, the buildings were acquired by the Brugnatelli family, who established their residence there. One of the descendants, Prof. Luigi, a professor of chemistry at this University for more than 40 years, left his assets to the Municipality for the benefit of the University. In 1954, after a complete renovation, it was inaugurated as a women's college, and in 1970, on the initiative of the then Rector, Prof. Malcovati, the adjacent building was purchased and renovated.

The HBIM documentation method outlined in this study is based on a predefined Scan-to-BIM workflow framework that converts point clouds into accurate models by generating, refining, and implementing components precisely aligned with the scanned data. The point cloud data collected through Terrestrial Laser Scanning (TLS) and Mobile Laser Scanning (MLS) at Collegio Castiglioni in Pavia, Italy, form the core geometric data for an HBIM workflow (Figure 2).

Although a point cloud consists of unstructured points, HBIM transforms this raw data into an intelligent, parametric 3D model. This is achieved by using the point cloud as a precise reference to create BIM objects—such as walls, columns, and vaults—that are both historically and architecturally accurate. These intelligent objects are further enriched with a wealth of historical information that goes beyond simple geometric data. Autodesk Revit was used as the primary HBIM authoring tool for parametric modelling, performance analysis, documentation generation, and high-quality visualisation. This includes captivating photographs, valuable archival documents, and extensive research detailing the construction and development of Collegio Castiglioni over the years. It provides a solid foundation for managing historic structures, planning conservation and restoration efforts, and supporting future analysis and maintenance of Collegio



Plate 1. A view of Collegio Castiglioni from Ex Alunne (college photo gallery)

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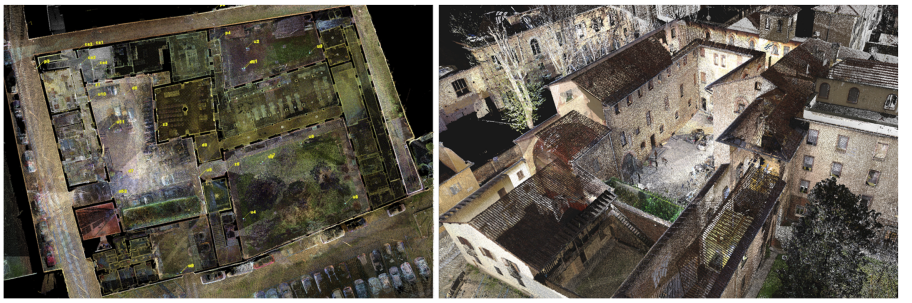


Figure 2. Result of 3D point cloud database from TLS and MLS in the digitization project of Castiglioni college, Pavia, Italy

Castiglioni. The reconstruction of 3D models and digital representations of historic buildings requires adopting appropriate techniques and technologies. Figure 3 shows the image of the "opening abacus" derived from the point cloud data of the Collegio Castiglioni, illustrating a key element for both HBIM and historical documentation. This highly detailed geometric representation, which depicts both the exterior and interior of the arch or opening, marks the first step in creating a sophisticated, parametric BIM object. This point cloud data also generates an HBIM object that accurately reflects the abacus's dimensions, shape, and placement and includes non-geometric information. This process connects laser-scanned physical structures with their historical context and metadata. The point cloud records the abacus's current condition, capturing details and flaws. Incorporating this data into an HBIM model makes it dynamic and accessible, supporting long-term management, analysis, and preservation. It provides a baseline for condition assessments, restoration plans, and environmental simulations.

The opening profiles and sectional representations presented in Figure 3 were extracted directly from the registered point-cloud dataset and subsequently converted into parametric HBIM objects within Autodesk Revit. These profiles document the geometric characteristics of doors, windows, arches, and openings, which constitute significant architectural features of the historic building. The generation of such profiles is essential for heritage documentation because it enables accurate recording of dimensions, construction geometry, architectural details, and conservation conditions. The extracted sections also support restoration planning, condition assessment, and future maintenance activities by providing measurable and information-rich representations of the building fabric. While the profiles were generated from high-resolution survey data, their accuracy depends on the quality of the point cloud, registration precision, and modelling tolerances. Consequently, the resulting HBIM objects represent highly accurate digital interpretations of the surveyed conditions while preserving the level of detail required for conservation and documentation purposes.

The macro modelling of the external and internal walls and elements is a fundamental step in the HBIM process for the digitization project of Collegio Castiglioni (Figure 4). This process directly utilizes the 3D point cloud database acquired from TLS and MLS. Macro modelling simplifies the management of large amounts of data by creating intelligent BIM objects for walls and structural elements. For instance, a macro-modelled wall is a "smart object" that includes key information from the point cloud data, such as material composition, historical modifications, and structural characteristics. This approach is efficient and scalable for large historical buildings like the Collegio Castiglioni, aligning with the Level of Detail (LOD) concept in HBIM to provide tailored detail for specific project goals. The macro-modeled walls and elements become the digital backbone of Collegio Castiglioni, creating a unified and easily managed repository of its historical, architectural, and structural data. This

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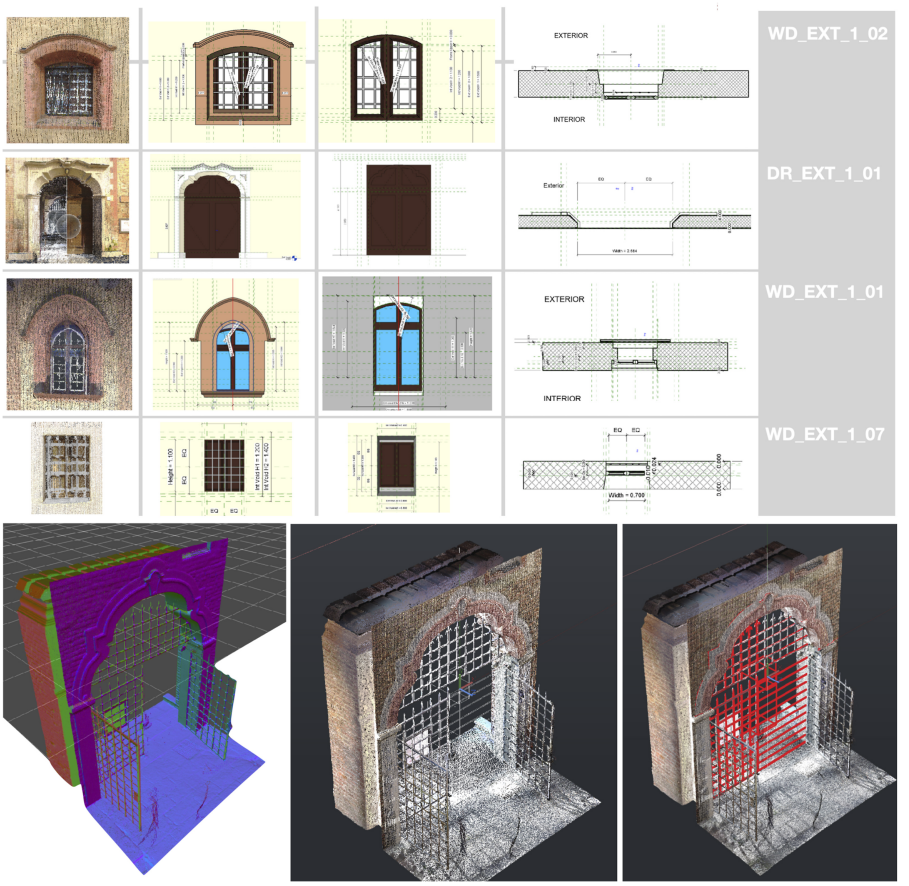


Figure 3. The opening abacus based on the point cloud



Figure 4. The macro modelling of the external and internal walls and elements

serves as an invaluable resource for long-term preservation and future analysis of the building's rich heritage.

Moreover, adherence to specific regulations and standardisation concerning classification, metadata, and the semantic aspects of heritage resources is imperative. Research and the

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development of standard protocols for surveying processes and data management in HBIM are needed to improve the effectiveness and efficiency of the approach (Argasiński and Piotr, 2023). Hence, efficient and consistent efforts are required to capture, manage, and provide detailed information on all these aspects, alongside integrating advanced information capture technologies. Such coordinated approaches are essential to ensure the accuracy, accessibility, and long-term usability of heritage data for effective conservation and management.

Conclusion

The documentation and preservation of cultural heritage are fundamental pillars in safeguarding our collective history, identity, and cultural legacy. Comprehensive and meticulous documentation forms the backbone of effective conservation, enabling a more profound understanding, appreciation, and informed management of heritage assets. Cultural heritage management is inherently complex, involving multiple lifecycle stages including identification, recording, conservation, and dissemination. Within this framework, Heritage Building Information Modelling (HBIM) has emerged as a vital digital tool that provides a permanent, multifaceted record of heritage buildings. The case study and reviewed literature demonstrate that HBIM can support the integration of structural, material, functional, historical, and semantic information within a unified digital environment. Over recent years, HBIM has transitioned from a primarily theoretical concept to practical application, with numerous projects worldwide demonstrating its ability to document, analyse, and manage historic buildings efficiently. This paper's comparative evaluation of leading HBIM software platforms reveals varied strengths and limitations, reflecting differences in usability, data integration capacity, accuracy, interoperability, and scalability. Such comparative insights highlight the necessity of aligning software capabilities with project-specific requirements, whether for detailed architectural documentation, archaeological data integration, or long-term conservation management. While some tools excel in precision modelling and complex geometry handling, others offer better user accessibility or enhanced compatibility with complementary technologies. Understanding these nuances empowers heritage professionals to make informed decisions, optimising HBIM deployment for diverse conservation goals.

As discussed in the literature, the integration of advanced technologies such as artificial intelligence (AI), machine learning (ML), deep learning, digital twins, neural networks, and Geographic Information Systems (GIS) significantly enhances the potential of HBIM beyond traditional digitisation. These innovations facilitate the processing and analysis of large, complex datasets, enabling remote and real-time monitoring of historic structures, predictive maintenance, and the automated generation of technical documentation that supports proactive decision-making. For instance, previous studies have shown that AI-driven image recognition and machine learning algorithms can help identify structural anomalies or material degradation, while GIS provides the spatial context essential for heritage site management. Digital twins create dynamic virtual replicas, allowing stakeholders to simulate interventions and assess their impact before physical implementation. This integrated, multidisciplinary approach maximises the precision, efficiency, and comprehensiveness of heritage documentation and conservation.

Additionally, these technologies promote greater collaboration among architects, conservators, engineers, researchers, policymakers, and communities, fostering shared responsibility and transparency. Proactive maintenance strategies, enabled by real-time data insights, reduce risks of deterioration and costly emergency interventions. Ultimately, adopting HBIM, complemented by cutting-edge digital tools and tailored software solutions, offers a robust, sustainable framework for preserving cultural heritage assets. It ensures that these irreplaceable architectural and cultural components are documented accurately, managed effectively, and preserved responsibly, securing their legacy for future generations.

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